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REPORT

CHARACTERISTICS OF TIPPING SCREENS
(carried out under OP 5439)

BY

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ABERDEEN PROVING GROUND
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CHARACTERISTICS OF TIPPING SCREENS
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Abstract

A series of light, metal plates, called "Tipping Screens", were fired at by caliber .30 and .50 projectiles. Tipping screens of duraluminum, steel, brass, copper and soft aluminum were tested at angles of impact from 0° to 60°. The yaw of the projectile was measured just prior to impact with the screen and for some distance beyond.

It was found that a relatively light screen will produce a large yaw, 40° to 60°, but that a distance approximately equal to 1/2 of an ordinary semiperiod is required for the yaw to develop. The yaw produced by the screen is independent of the angular velocity and yaw of the projectile at the time of impact. It depends on the material, thickness, and angle of impact of the screen, and the physical properties of the projectile. The variation of tipping with thickness and angle of impact is complex, and cannot be given by a simple formula. The optimum material of those tested is duraluminum; however, the steel shows promise of equaling the performance of the duraluminum if its strength-weight ratio is increased sufficiently. A mechanism by which the screen tips the projectile is proposed, and the results are analyzed in accordance with this hypothesis.

INTRODUCTION

1. PHILOSOPHY OF TIPPING SCREENS:

The yaw of a projectile is greatly increased after the projectile penetrates a dense obstacle placed in its path. A delicate balance exists between the stabilizing and destabilizing forces acting in normal flight, and any impulsive forces of the magnitude involved in solid body impact must upset this balance completely during the interval in which the bullet passes through the obstacle.

If the projectile strikes armor plate after being yawed, its ability to penetrate the plate is reduced in proportion to the amount of yaw. The projectile in yawed flight presents a much larger projected area to the armor plate than in head-on flight and has to punch a correspondingly larger hole in order to penetrate completely. The increase in effective ballistic limit with increase in incident yaw is quite similar to the increase in ballistic limit with angle of impact.

The two effects mentioned above combine to suggest a type of armor plate which, if properly constructed, would be superior weight for weight to the usual solid plate. A relatively light piece of armor would be placed so as to intercept the bullet first. Its function would be to impart a sufficiently large impulsive couple to the projectile so that its first maximum yaw would reach an amplitude of some 50 degrees or greater at the half period beyond the tipping screen. Speaking loosely, it would "tip" the bullet. Because of this unique function, this front light armor plate is called a "tipping screen". Beyond the tipping screen a heavy piece of armor would be placed at the position of maximum yaw to actually stop the projectile.

The function of the tipping screen and the armor plate are entirely separate. This distinction should be clearly understood in order to appreciate the philosophy behind composite armor of the type proposed. The tipping screen serves only to impart a sufficient impulsive torque to the projectile to increase its maximum yaw to a high value. It is not intended to retard or damage the projectile, though this may occur incidentally. The armor plate is relied upon to stop the projectile. Consequently, the tipping screen should be only heavy enough to carry out its tipping function.

2. SELECTION OF MATERIAL:

One might suggest many materials which would serve this purpose, but little experimental evidence is available on which to base an intelligent selection. To the author's knowledge, no quantitative research has been carried out prior to the present investigation. In view of this lack and the fact that the problem falls primarily into an engineering category, a purely empirical method of attack is quite justified.

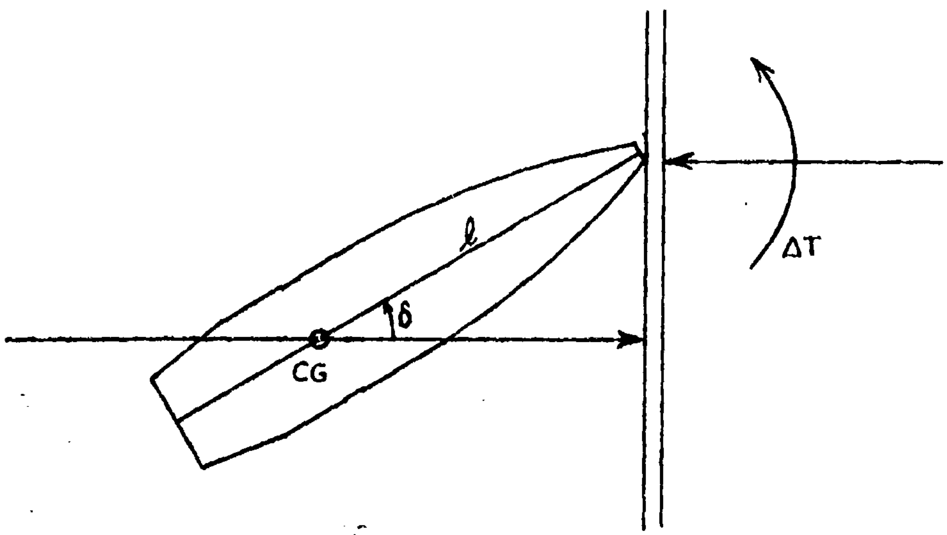
3. ORIGINAL HYPOTHESIS:

However, before starting on the extensive program that the empirical method demands, it was felt worthwhile to see whether the behavior of the tipping screen might be predicted partly on a theoretical basis.*

As the projectile approaches the tipping screen, it is inclined at some small angle of yaw, to its direction of motion. If the screen is normal to the projectile's trajectory, then it is possible to visualize an impulsive couple ΔT, acting on the projectile, given by

$$\Delta T = f \, l \sin \delta_o$$

where δ_o is the yaw on striking the screen, hereafter designated as the "initial" or "incident" yaw, l is a characteristic length, and f is a factor of proportionality, as illustrated in the accompanying sketch.



* Mr. R. H. Kent and Mr. H. P. Hitchcock suggested the original hypothesis. Refer to Ref. No. 1.

The amplitude of the yaw beyond the tipping screen would be roughly proportional to the impulsive couple and hence, to the initial yaw, if the amplitude of the yaw beyond is large compared to normal; that is:

$$\delta_m = k\,\delta_o$$

where δ_m is the value of the first maximum yaw beyond the screen and k is a constant the value of which depends on all the other parameters involved.

If experimental conditions are held constant from one material to the next, that is, if the caliber and velocity of the projectile and the weight per unit area and angle of impact of the screen are kept the same but only the material from which the screen is made is changed, then k is a figure of merit of the tipping screen's behavior. The screens having the greater k would have the better performance. To select the optimum material, it should only be necessary to test a number of equal weight screens of the materials appearing to have the greatest promise and to determine the one with the largest k.

It is appropriate to mention at this point that the experimental evidence obtained proved that this hypothesis is incorrect, at least for small yaws. However, since this hypothesis justified part of the experimental technique used and appeared to be plausible and concise, it merits an adequate discussion even though incorrect.

The determination of k required an accurate measurement of the yaw before and after the tipping screen. The yaw after was large and was easily measured by yaw cards. The yaw before was small and measurements from yaw cards would be subject to considerable error. In view of the direct dependence of k on the value of δ_o, large errors in δ_o could not be tolerated. Consequently, δ_o was measured from spark photographs taken directly in front of the tipping screen.

4. SELECTION OF SHAPE:

In addition to the optimum material for the tipping screen, the optimum shape is required. The increase in the ballistic limit of armor plate with angle of impact suggests that the tipping screen might prove more effective inclined at some angle to the trajectory. In many places in aircraft, it is feasible to incorporate the tipping screen into the structure inclined at an angle to the principal direction of attack and thus use a lighter screen than one placed at normal. For example, the skin itself may prove effective as a tipping screen. Of course, the projected weight of the screen increases with its angle of obliquity but the possibility exists that the resultant tipping increases faster than the projected weight. Consequently, the tipping screens were tested at a series of angles of impact ranging from normal to 60°.

5. SPACE LIMITATION:

One stringent limitation of the tipping screen-composite type of armor is immediately apparent. The tipping screen does not tip the projectile to any appreciable angle of yaw as it penetrates the screen. It merely imparts an impulsive couple to the projectile. The impulsive couple expends itself by increasing the normal yaw. As a consequence, the yaw requires considerable distance before it reaches an effective value.

The reaction between the impulsive couple and the projectile is analogous to the response of a weight suspended by a spring to a sharp blow. The blow is finished before the weight has moved appreciably, but the energy of the blow gives the weight sufficient momentum to carry it to a considerable displacement against the pull of the spring. The displacement takes place in a normal half period. Similarly in the case of the projectile after penetrating the tipping screen, the maximum yaw develops in a distance that is, the order of magnitude of a normal half period. In contra-distinction to the case of the spring, the period depends inversely on the amplitude of yaw (to be discussed later), that is, the larger the yaw the shorter the period. In the case of a caliber 0.50 projectile, a 50° amplitude of yaw shortens the half period from 12-1/2 feet to approximately 5 feet. Even so, the tipping screen must be placed a distance of 4 to 6 feet in front of the armor plate to work effectively.

In many military applications, the space required between screen and armor would not be allowable. Aircraft are a unique exception. The direction in which they are most vulnerable to attack is from the tail. The fuselage having many transverse structural members permits the armor to be spread out along its length and thus in the proper direction for the most effective protection. Furthermore, there is the possibility that the tipping screen might serve the dual purpose of both screen and structural member.

6. PURPOSE OF PRESENT INVESTIGATION:

The purpose of the present investigation is the determination of the basic factors governing tipping screen performance. The significant parameters were (and, for the exception of No. 1, are) believed to be:

(1) the initial yaw of the projectile,
(2) the caliber of the projectile,
(3) the material of the tipping screen,
(4) the thickness of the tipping screen,
(5) the angle of impact between the normal to the screen and the tangent to the trajectory.

The influence of these parameters was systematically investigated over a limited range of values. Within this range the results are believed to be accurate and consistent. Outside this range, only the most qualitative extrapolations can be made. This investigation has disclosed certain general trends. For practical design, the results should be applied only within the limits covered. In the opinion of the author, one should approach the problem of tipping screens with the philosophy that the basic laws governing their action are not known well enough as yet to be expressible in a consistent and comprehensive set of mathematical formulae and that each particular case must be investigated empirically on its own merits.

EXPERIMENTAL APPARATUS AND TECHNIQUE

1. RANGE:

The firings were carried out in a small enclosed range which could be darkened for the taking of spark photographs. The apparatus was placed in position along the level cement floor and held stationary by lead weights. The general arrangement is sketched in Figure 1.

2. GUN AND GUN MOUNT:

A Mann accuracy type rifle was used. It was fired from a conventional V-block, mounted in a Frankfort rest, which in turn was held the desired height from the floor by a heavy table. An elementary recoil mechanism consisted of two springs fastened together at one end to the trigger guard and fastened separately at the other to chords passing over pulleys and tied to 5-pound lead weights. The setup for caliber 0.30 Mann Barrel and V-block is shown in Figure 2.

Caliber 0.30 and 0.50 Mann barrels and V-blocks were used. Each V-block was aligned before firing so that the center line of the bore was accurately horizontal and approximately parallel to the walls of the range. The alignment was checked frequently but in all cases any changes were found to be of second order magnitude.

3. AMMUNITION:

Two types of projectiles were fired, the caliber .30 M1922 A.P. and the caliber .50 M1 A.P. Service ammunition was used. The velocity was not measured, however, for it is believed that small differences that might occur from round to round in the service ammunition would have not appreciable influence in the tipping. The muzzle velocities are approximately:

Caliber 0.30, M1922 A.P.: 2750 ft/sec

Caliber 0.50, M1 A.P. : 2660 ft/sec

The effect of velocity on the tipping was not investigated, though this probably is important if the velocity is different from service.

For each configuration a group of from four to ten shots was fired. All experimental conditions were kept constant during the firing of the group. The shots of the group were fired one after the other with only enough delay to change the yaw cards, armor plate, and spark photographs.

4. TIPPING SCREEN:

The tipping screen consisted of a sheet of metal one foot by three feet. It was held in position in a steel frame which could be rotated about a horizontal axis. The steel frame without the tipping screen can be seen in Figure 4 between the spark photography apparatus and the yaw card frames. In this photograph, the frame is inclined at 60°. Before firing, the axis of the frame was leveled and turned until it was accurately perpendicular to the trajectory. The technique used for this latter adjustment will be discussed in the section on the spark photography apparatus. By rotating the steel frame about the horizontal axis the sheet could be set accurately at any desired angle of impact by a bevel protractor and level, since the trajectory is horizontal. The steel frame was set at the desired angle and held there until a group of shots was fired. Between each shot the tipping screen was shifted in the frame so that a space of four inches or more was left between bullet holes. The sheet was supported along its three foot sides and at one foot on either side of the center of impact. This type of support held the sheet quite rigidly. Penetration was a local affair and no general deformation of the sheet was observed. This is discussed in detail in the section on the Mechanism of Tipping.

Prior to this investigation, no information was available on the characteristics of a material which would best suit it for use as a tipping screen. The two physical properties which appeared to have the most importance, at least for tipping screens in aircraft, are tensile strength and weight per unit area. The four extreme combinations of these two properties were met by the following materials:

Light Weak: Pure aluminum, soft, 1/8" sheet

Heavy Weak: Pure copper, hard, 1/8" sheet
Brass, hard, 1/8" sheet

Light Strong: Duraluminum, 24 ST, 1/16" sheet, 1/8" sheet

Heavy Strong: Czeck Helmet Steel, 0.047" sheet, properties unknown

Mild steel, 1020, 0.0475" sheet,

0.0951" sheet.

The physical characteristics of the materials tested are given in fig. 5.

No information was available on the necessary thickness of these materials to produce sufficient tipping, but, since the 1/16" and 1/8" dural sheet were available and looked promising, they were tried first. As they worked satisfactorily, other materials were based on the dural results. The 1/8" soft aluminum, Czech helmet steel, and 0.0475" mild steel have close to the same weight per unit area as the 1/8" dural. The 0.0951 mild steel has the same weight as 1/4" dural. The brass and copper have the same weight as 3/8" dural. The original plan was to test 1/4" and heavier dural sheet. Due to failure of the Air Corps to secure a sufficiently high priority, the heavy dural was never supplied to the Proving Ground. The significance of this lack will be discussed in the section on 1/8" dural results.

The steel did not have sufficient tensile strength to make it a truly representative example of the strong-heavy class. Its strength-weight ratio is less than 1/3 that of the dural and is, in fact, little better than the brass. A steel having a tensile strength of 209,000 lbs. per sq. in. would have had the same strength-weight ratio as the dural. Unfortunately, the Proving Ground was unable to obtain steel sheet having the desired strength.

The range of angle of impact investigated was from 0° to 60°, the angle of impact being defined as the angle between the normal to the tipping screen and the tangent to the trajectory. Tests were carried out at 0°, 20°, 40°, and 60°. However, not all the materials were tested throughout the entire range. Where it seemed sufficient, tests were carried out at one or two angles only.

For the initial firings of caliber 0.30 against 1/16" and 1/8" dural tipping screens, the screen was located 8-1/2 feet down-range from the gun muzzle, the distance of a normal half-period. If the theory is correct, this should be the position of maximum yaw. The firings were repeated with the screen placed at 17 feet down-range, the position of minimum yaw. From an analysis of the results (discussed in the section on the Effect of Incident Yaw), it is clear that the position of the screen along the trajectory is immaterial. For consistency, however, all subsequent firings were conducted with the screen at the minimum yaw position, 17 feet for the caliber 0.30 projectile and 25 feet for the caliber 0.50 projectile.

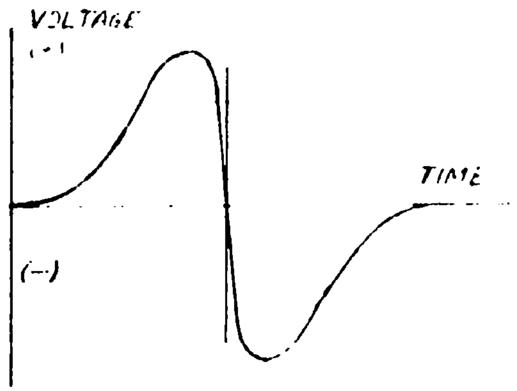
The statement regarding the independence of the results from the position of the screen along the trajectory should be qualified by the remark that only the yaw of the projectile in normal flight has no influence on the tipping. As the screen is placed farther and farther out along the trajectory the velocity diminishes and at some position this change will become important. Before setting a limit on the distance that the screen may be placed away from the muzzle before its tipping is affected appreciably, an investigation of the effect of velocity must be carried out.

5. SPARK PHOTOGRAPHY EQUIPMENT

The spark photography apparatus was placed between the gun and the tipping screen. When the incident yaw was to be measured, spark photographs were taken 10 to 12 inches before the tipping screen. When the incident angular velocity was to be measured, spark photographs were taken at the position of the maximum yaw between the gun and the screen. The spark photography apparatus is to be discussed fully in a future report, but for the moment a brief outline of its operation will suffice.

The spark photography technique consists essentially in generating a brilliant but extremely quick burst of light which casts a shadow of the flying projectile on a photographic film. The general arrangement is sketched in Figure 1 and a photograph is shown in Figure 4. In the photograph the two high voltage spark units are sitting on the right side of floor of the carriage and on the bench on the left of the carriage; the shutters over the light tubes clearly identify these units; the pick-up stage topped by the antenna post and antenna proper sits on a shelf at the right of the carriage; the slide frame holding the photographic film packs is located above and to the right of the antenna; the film is placed parallel to the trajectory and 2 inches or so to one side; one light source is placed opposite the film 40 inches or so on the other side of the trajectory; a second light source and film are placed at right angles to the first, thus obtaining projections of the projectile in two orthogonal planes. The light source consists of a short spark gap in series with a mercury flash tube and a 1/2 microfarad condenser charged to 6000 volts. The circuit and component parts are given in Figures 6, 7, and 8. When the mercury flash tube is ignited by a triggering voltage, the condenser discharges through the flash tube and spark gap in a microsecond or two, thus producing in the spark gap a spark of great intensity and of such short duration that it effectively "stops" the projectile. A rough calculation indicates an initial current of 7000 amperes. The 6000 volts are generated by a conventional vacuum tube rectifier. After discharge, the condenser recharges through a large resistor. A thin metal diaphragm with a No. 72 drill hole is placed in front of the spark gap. All the light from the spark reaching the film must come through this hole. The hole is so small that the light from the spark behaves as though it comes from a point source. The efficiency of such an arrangement is poor but the image of the projectile is sharp and there is sufficient light to obtain satisfactory contrast on Eastman Super-speed, portrait film.

The trigger voltage is generated in the following way: an electrostatic pickup is placed in the path of the projectile; the normal voltage impulse versus time curve, crosses the axis a short distance after the projectile has passed through the antennae loop, and a rectifier in the circuit is arranged so that only the second hump of the voltage impulse is passed; this second hump ignites a neon strobotron which discharges a condenser through the primary of an Aberdeen spark coil; the high voltage surge from the secondary ignites the mercury flash tube. Thus, a short distance after the projectile has passed through the antennae loop the 6000 volt condenser discharges through the spark gap, and the light from the gap silhouettes the projectile on the film.



The rectifying stage passes a surge of one sign only. The sequence of sign of the two humps of the voltage curve, + to − or − to +, depends on the sign of the charge on the projectile. The rectifier is switched so that it will pass the second hump of one sequence only. The majority of the projectiles fired have the same sign and the trigger circuit works properly, firing the high voltage spark at the beginning of the second hump when the projectile has passed through the antennae loop and is in front of the photographic films. However, a few of the projectiles come from the gun with the opposite charge, for reasons which are discussed in reference 2 (but which are considerably in question in view of certain unpublished data obtained recently at the Proving Ground). For these rounds, the rectifier passed the first hump, generated when the projectile was in front of the antennae, and the spark was triggered prematurely resulting in a blank photograph. 18% of the rounds were lost in this way; the caliber 0.30 behaved in a more uncertain manner than the caliber 0.50. It is appropriate to mention that a circuit has since been constructed at the Proving Ground which will operate properly on charges of either sign, but, unfortunately, it was not available at the time of these tests.

In addition to the shadow of the projectile, the shadow of the surrounding shock wave system is also cast on the film. The reasons for this and the significance of the shock wave system are discussed in references 3, 4 and 5. The wave system has no direct bearing on the present problem, however.

As can be seen from the preceding description, the spark photography apparatus consists of four component parts: an antennae pickup stage, an amplifier with a rectifying stage, two high voltage units containing the spark gaps, and two photographic films mounted in a suitable holder. A single spark photograph gives a projection of the projectile in only one plane. As mentioned previously, in order to obtain a space orientation of the projectile, two high voltage stages and photographic film holders are placed at right angles. The two spark units are triggered simultaneously from the pickup by connecting the igniting bands on the two mercury flash tubes in parallel to the secondary of the Aberdeen Spark Coil (See Figure 6). From the two orthogonal projections of the projectile, a simple trigonometric calculation gives the angles of yaw and orientation (see page 15).

The photographic films are held in conventional plate holders or in film packs which are held in turn at right angles to one another in a slide frame. 8" x 10" cut film and 5" x 7" film packs were used. A close up of the film packs in the slide frame is shown in Figure 9. The slide frame is mounted in turn on the superstructure of a carriage sitting on the floor of the range. The carriage superstructure holds the various components of the spark photography apparatus in proper alignment. The slide frame is adjusted so that the films are held in horizontal and vertical planes respectively, approximately parallel to the trajectory, and so that the projectile passes in the corner between the two, about 4 inches away from both plates.

In order to measure the projected yaw of the projectile in the vertical and horizontal films, it is essential to have a reference line giving the horizontal and vertical projections of the trajectory. The measurements were made so close to the muzzle that a projection of the initial tangent to the trajectory was believed sufficiently accurate to measure the yaw from. Furthermore, since a Mann accuracy barrel was used, it was assumed that the initial tangent was coincident with the center line of the bore.

The conventional method for projecting the center line of the bore is to use a surveying telescope concentrically mounted in two identical spacing rings. As will be seen this method was not feasible in the present case, because the vertical and horizontal projections of the center line are desired rather than the location of the center line itself. The method used is illustrated in Figure 10. A vertical projection of the center line or rather a line parallel to the center line can be made by using an alidade sitting on a plane table with the rule edge of the base parallel to the center line. A close up is shown in Figure 3. A dummy Mann barrel has two coplanar, parallel bars pinned in transverse slots in the fore and aft spacing rings, respectively, so that their fore and aft edges are accurately perpendicular to the center line of the barrel. The dummy barrel is placed in the V-block and the plane of the cross bars is leveled, using a Starrett 12" machinist's level. Each bar, incidentally, was ground accurately square and straight prior to its assembly in the dummy barrel. Another precisely machined bar was pinned to the underside of the alidade base so that its long edges were accurately perpendicular to the rule edge of the base. The alidade was placed on the cross bars of the dummy Mann barrel with its cross bar snug against the aft edge of the forward Mann barrel cross bar thus bringing its rule edge parallel to the center line of the dummy Mann barrel. Since the base of the alidade is horizontal the optical axis of the telescope traverses a vertical plane. Consequently, since the rule edge is parallel to the axis of the barrel and lies in the plane swept by the optical axis of the telescope, the vertical plane surveyed by the alidade is a vertical plane parallel to the center line of the bore.

Two reference wires are mounted on the slide frame, one in front of each film, so that its image is cast on the film along with the projectile's image. The mountings for the reference wires consist of screw devices constructed so that each end of each wire can be adjusted laterally. The mountings can be seen in Figure 9 with the wires in place. The mountings on the vertical film holder are slotted, grooved eccentric wheels; the mountings on the horizontal film holders are screws held in yokes. The wire in front of the film in the vertical plane is leveled with a Starrett 12" machinist's level. Since the Mann barrel is also level, this wire is a true horizontal projection of a line parallel to the trajectory. The wire in front of the film in the horizontal plane is aligned with the alidade in position on the dummy Mann barrel. The two ends of the reference wire pass in a groove over the mounting screw and hang vertically, weights being attached to the ends. The alidade is slid along the cross bars until the two hanging ends are seen one end on one side of the vertical cross-hair and the other end on the other side of the cross-hair (see detail sketch in fig. 10). The two ends of the reference wire are then adjusted until they both coincide with the vertical cross-hair. In this way, they both lie in the vertical plane surveyed by the alidade, and, hence, the reference wire itself is a true vertical projection of a line parallel to the trajectory. No attempt was made to locate the actual trajectory itself. It was necessary to measure only the yaw. The drift was of no concern in the present investigation.

A procedure similar to the one described above was used to place the axis of the tipping screen frame perpendicular to the trajectory. The screen was set at 0° angle of attack and adjusted so that it lay in a vertical plane. A square was then held against the screen and moved laterally until its side perpendicular to the screen could be seen in the field of the alidade. The frame was rotated about a vertical axis until the length of the perpendicular edge coincided with the vertical cross hair in the alidade. At this position the vertical plane of the screen was perpendicular to the trajectory, and, hence, the axis of the frame was aligned both horizontal and perpendicular to the trajectory.

In order to positively identify each spark photograph with its corresponding round number, a set of numbers about 1/2" high were made from wire and soldered on the end of small metal tabs. A strip of cellulose tape was stretched across the slide frame in front of each film slightly to one side of the reference wire. The tabs on the numbers were stuck to the tape, holding the numbers in proper order to one side of the reference wire.

Each spark photograph shows the silhouette of the round number, the reference wire, the projectile, and the shock wave and wake system. Representative photographs are shown in Figures 11 to 18. On the photographs the projected yaw was measured from the side of the projectile to the reference wire by a Brown and Sharpe draftsman's protractor having a 5 minute vernier. The accuracy of the yaw measurements, estimating from all the probable sources of error, is good to within $\pm$ 10 minutes. If ξ is the yaw measured from the film in the horizontal plane and η the yaw in the vertical plane, then δ, the angle of yaw, and φ, the angle of orientation, are given in the first quadrant by

$$\tan \delta = \sqrt{\tan^2\eta + \tan^2\xi}$$

$$\tan \varphi = \tan\xi / \tan\eta$$

Appropriate changes must be made in the calculation of φ in the 2nd, 3rd, and 4th quadrants.

In addition to the spark photographs taken under the conditions just described, a series of pictures were taken of the caliber .50 projectile penetrating a 1/8" dural screen inclined at 60° (see Figs. 19 to 27). The screen was supported at the top and bottom only. The spark unit was placed on one side of the screen and the film holder on the other side so that the plate cast its shadow across the film. A series of rounds was then fired. The spark for each round was timed a little later than the preceding round, and the screen was shifted in its holder between rounds so that each round struck an undisturbed section. Thus a series of pictures were obtained showing the projectile at successive positions during its penetration of the screen. The impact of the projectile on the screen generated a flash of light which in certain cases fogged the film. A number of pictures are partially obscured by this extraneous light.

Since each picture shows a different projectile, the series should not be regarded as a motion picture of the action taking place during penetration. Each picture shows a unique situation. The series as a whole represents a case history of the phenomenon.

A similar series of spark photographs were taken of the caliber .30 projectile penetrating a 1/16" dural screen inclined at 60°. The photographs are very similar to the caliber .50 - 1/8" dural series, and, since they reveal nothing new, they are not included in this report.

6. <u>YAW CARDS</u>:

Beyond the tipping screen, yaw cards were placed at 1 ft., 2 ft., 4 ft., 6 ft., 8 ft., and 10 ft. (See Figure 1 and, for a down-range photograph, Figure 4). Photographic paper, 14" x 17", was used, and from 2 to ? shots could be recorded on a single card. The plane of each of the cards was adjusted normal to the trajectory. The right edge of the supporting frame was adjusted to a true vertical position and used as a reference line. The yaw and orientation were measured from the major axis of the hole punched in the card. The technique is outlined in reference 6 and representative samples of the holes are shown in fig. 29.

One source of uncertainty in the yaw card measurements appeared after the firings were under way. The projectile is deformed in penetrating the tipping screen. If the screen is heavy enough or at a sufficient angle of impact to produce considerable tipping, the nose of the jacket is usually flattened somewhat, and occasionally torn well back and to one side. Some of the rounds had the jacket stripped completely off the core by the tipping screen. This deformation shortens the length of the projectile, and the major axis of the hole in the yaw card no longer gives a correct measure of the angle of yaw. Furthermore, it is impossible to determine from the yaw cards the exact amount of each deformation. It is possible to set limits, which are, of course, the uninjured projectile on the one hand and the core on the other, and from these limits to make a rough estimate of the possible error in the measurement of the yaw from a particular hole in the yaw card. At high yaws, however, this maximum possible error may be very great, so the person measuring the cards had to rely on his own judgment in questionable cases.

In addition to affecting the measurements of yaw, the deformation changes the whole behavior of the projectile. After impact with the tipping screen the projectile no longer is a symmetrical body of revolution, but rather is an irregular slug traveling down-range. The yaw down-range from the screen could have been much more accurately determined from spark photographs taken with reflected light and cameras in place of the yaw cards but such a technique will not be available at the Proving Ground for six months or a year.

In spite of the above mentioned sources of error, it is believed that the yaw measurements are good to $\pm$ 10%. Certainly the comparative results are that good. If anything, the measurements of yaw err on the side of being too small. The curves representing the basic results were faired smoothly through the points to give the most probable sense. On the other hand, the curves taken from the mean values of the basic results, are drawn accurately through the mean values themselves.

In certain representative rounds, a new card was placed one inch behind the tipping screen and parallel to its surface. Most of the splash coming from the screen left its mark on this "splash" card. Illustrative examples are shown in Figures 29 to 32.

RESULTS

1. PURPOSE AND METHOD OF PRESENTATION:

The purpose of the present investigation was (1) to determine the laws governing the basic behaviour of tipping screens and (2) to select the optimum material and angle of impact for tipping screens used against caliber .30 and caliber .50 projectiles. The experimental technique and the materials used to achieve this purpose have already been discussed. Unfortunately for any directness and simplicity of presentation, the results show that the behaviour of tipping screens is complex and cannot be explained by a few sweeping generalizations. First, the results pertaining to the original hypothesis concerning the relation between the incident and resultant yaws will be presented. Second, there will be described a general picture of what is believed to be a correct analysis of the mechanism by which tipping is produced. Third, the results of the tests on individual screens will be discussed.

Before continuing further, it will be well to define a few terms.

Incident yaw: the incident yaw, also called the initial yaw, is the yaw measured from the spark photographs taken one foot (approximate) in front of the tipping screen. The variation in yaw between the photograph and the screen is so small that the incident yaw can be taken for all practical purposes as the yaw of the projectile just as it strikes the screen.

Resultant yaw: the resultant yaw is the value of the first maximum yaw beyond the tipping screen.

Incident orientation: the incident orientation is the orientation of the projectile just as it strikes the screen.

Resultant orientation: the resultant orientation is the orientation of the projectile just after penetrating the screen. (The distinction between the meanings of "resultant" describing the yaw and describing the orientation should be noted).

Angle of impact: the angle of impact is defined as the angle between the tangent to the trajectory and the normal to the screen. The angles of impact are usually designated by 0°, 20°, 40°, and 60°. However, a screen at an angle of impact of 0° may also be called a "normal" screen or a screen "at normal".

Angular velocity: the term angular velocity as used in this report is defined as that component of the angular velocity perpendicular to the axis of the projectile.

2. EFFECT OF THE INCIDENT YAW AND ANGULAR VELOCITY:

The results concerning the incident yaw are presented in the form of a plot of the incident yaw against the resultant yaw (see figs. 33 to 38). Each point represents a single shot. Each graph represents a group of shots fired under constant conditions. The variation in incident yaw from shot to shot is due to slight variations in the launching of the projectile from the gun.

The complete lack of correlation between the incident and resultant yaw for all of the groups is clearly evident. In particular the points for the groups fired at zero angle of impact are dispersed in a random manner about their mean.

These results prove that the incident yaws of the magnitude encountered in the normal flight of the projectile have no effect on the resultant yaw. If the theory for k is correct, as discussed in the introduction, the points for each group of shots should lie about a line through the origin having the slope k. The actual distribution is random and definitely not linear. Consequently, the k hypothesis must be false.

In addition to a yaw the projectile also has an angular velocity, and it was proposed that the angular velocity might be a determining factor. This possibility was investigated by taking spark photographs at the position of maximum yaw and placing the tipping screen at the position of minimum yaw. The method is discussed in detail in appendix No. 1. To a first approximation the angular velocity at minimum yaw is directly proportional to the amplitude of the maximum yaw. If the angular velocity influences the tipping, a correlation must exist between the yaw at the position of maximum yaw before the screen and the resultant yaw. The results are shown in figs. 39 and 40. The lack of correlation is immediately apparent, and the angular velocity as well as the initial yaw is eliminated as an active parameter.

Although the results show that the initial yaw and the angular velocity do not influence the tipping, it is the author's opinion that their negative effect holds only so long as the magnitudes of the initial yaw and angular velocity are small. If the projectile were yawed to a considerable amplitude by some cause before striking the tipping screen, it is believed that the large initial yaw would have a proportionally large effect on the tipping.

The negative effect of the initial yaw and angular velocity simplifies the investigation to a certain extent. Since these two do not influence the tipping, they need not be measured in an ordinary tipping screen investigation. For firings with a normal projectile in normal flight, the screen may be placed at any convenient location along the trajectory provided it is not too far from the gun, and only the yaw beyond the screen need be measured. Tests can be carried out on actual prototypes of aircraft with tipping screen armor installed without the need of an elaborate spark photography technique.

3. MECHANISM OF TIPPING:

a. Purpose

Any general theory based on broad assumptions concerning the physical character of the reaction between screen and projectile appears inadequate to explain the results for different materials, angles of impact, and caliber. The results at first glimpse seem contradictory or at least motivated by obscure and complicated causes. For example, the dip in the caliber .30 - 1/16" dural - angle of impact curve at 40° and the complete change in the character of the variation with angle of impact for the caliber .30 when the thickness of a dural screen is increased from 1/16" to 1/8" (see fig. 70) are most mysterious. Furthermore, it is hard to explain the failure of the initial hypothesis concerning the dependence of the tipping on the incident yaw.

The weakness of a general theory usually lies in its being based on an idealized case. The behaviour of tipping screens cannot be idealized satisfactorily. It is hardly necessary to remark that the entire effect of the screen is imparted to the projectile during the brief instant in which the projectile breaks its way through the screen. Yet a close examination of the process that takes place during penetration gave the only plausible explanation of the tipping phenomena. In manner in which the metal ruptures letting the projectile through appears to control the tipping produced. The details of the process are in satisfactory agreement with the results from the spark photographs and yaw cards. The nature of the penetration will be discussed first and the individual cases later.

b. Experimental Evidence

Three sources of experimental evidence are available. First, a series of pictures of the caliber .50 projectile penetrating the 1/8" dural at 60° had been taken, as was discussed in the section on Experimental Results (see figs. 19 to 27). Second, a careful examination was made of the hole, left by the projectile in the screen.

Photographs were taken of the front and rear views of the hole. In order to orient the screen with the trajectory, a vertical line was scribed on the screen through the center of the hole. Up is indicated by the mark of an arrow on the line. For those rounds in which the screen was placed at normal, a second line was scribed in the direction of the plane of orientation. The hole was then sectioned along this line and a photograph was made of the section. The three photographs give a complete three-dimensional record of the hole (see figs. 41 to 45). Third, the orientation of the projectile was calculated just before and just after penetration. The incident angle of orientation is computed by adding the orientation measured from the spark photograph and the change in orientation that takes place in the distance between the photograph and the screen. The resultant angle of orientation is computed by extrapolating the measurements up range from the yaw cards to the screen. The incident and resultant orientation are plotted together on a polar coordinate graph. The polar angle is taken equal to the orientation. The radii of the incident and resultant orientation are made equal, but otherwise the radius is arbitrary. It is so chosen that the data will not overlap and can be seen clearly at a glance (see figs. 46 to 49).

c. Rate of Reaction

The speed at which the projectile drives its way through the screen effects the nature of the reaction profoundly. The caliber .30 A.P. traveling at 2600 feet per second takes only 40 microseconds (0.000040 sec) to completely penetrate the screen. A mass moved 0.01" in this time would require an acceleration of 30,000 g (the acceleration of gravity). As a consequence, the screen is stiffened by its inertia as well as by its own inherent strength. The mass to be displaced increases with the distance from the point of impact. This increase localizes the break, and, in fact, a short distance away from the hole the material can be regarded as rigidly supported.

The projectile is usually much heavier than the metal of the screen that it displaces. The screen will yield and give way, and any displacement of the projectile, either lateral or rotary will be minute during penetration. As discussed in the introduction, the reaction of the screen on the projectile is primarily impulsive. No tipping takes place at the screen. The tipping develops beyond the screen as the result of the impulsive couple at impact. On the other hand, the section of the screen adjacent to the trajectory will be given a violent acceleration. The pieces that break away will leave the screen with a velocity comparable to that of the projectile. The sections that remain will be given an impact energy that will carry them well beyond their position at the instant the projectile has passed completely through.

The rigidity of the material plays an important role in the type of penetration. The rigidity comes, of course, not only from the inherent static rigidity of the sheet but also from the additional inertial resistance of the sheet to displacement. For this reason, the screen is much "stiffer" under dynamic impacts than under static loads.

d. Classification of Screens

All screens coming within the scope of this investigation could be placed categorically in one of two classes: flexible or rigid. The distinction is fundamental but, at the present state, must be made on a pragmatic rather than a dimensional basis. Roughly speaking, a screen can be classed as flexible or rigid depending on whether the mass of the screen involved during impact is light or heavy compared to the projectile. The behaviour of the two types is the best criterion for distinguishing them. With the screen placed at normal, the flexible type will show a failure broadly described as an "orange peel". The metal ruptures in shear along radial lines and the individual pieces bend back letting the projectile through to form a crown or "orange peel" on the rear surface. On the other hand, the rigid type shows none of the radial shear and bending failure at normal impact. The material around the hole yields in compression letting the projectile through similar to the manner in which a die pierces a heavy billet. The sides of the hole are smooth and free from cracks. A small crown is formed at the rear, but this comes from the material of the rear layers of the hole and not from any general orange peeling.

There are two reasons why the "flexible" or "rigid" classification is essential: first, the dependence of the tipping on the angle of impact is fundamentally different in the two classes; second, a proportionally great increase in the tipping produced at zero angle of impact takes place in passing from the flexible to the rigid class.

One of the purposes of the present report is to select the optimum screen on the basis of projected weight. This involves a knowledge of the variation with thickness as well as with angle of impact. If in increasing thickness at normal to meet the projected weight at a high angle of impact, the screen passes from the flexible to the rigid class, the results will appear contradictory to those for smaller thickness, unless account is taken of the change in regime.

e. Penetration of Flexible Screens at Normal

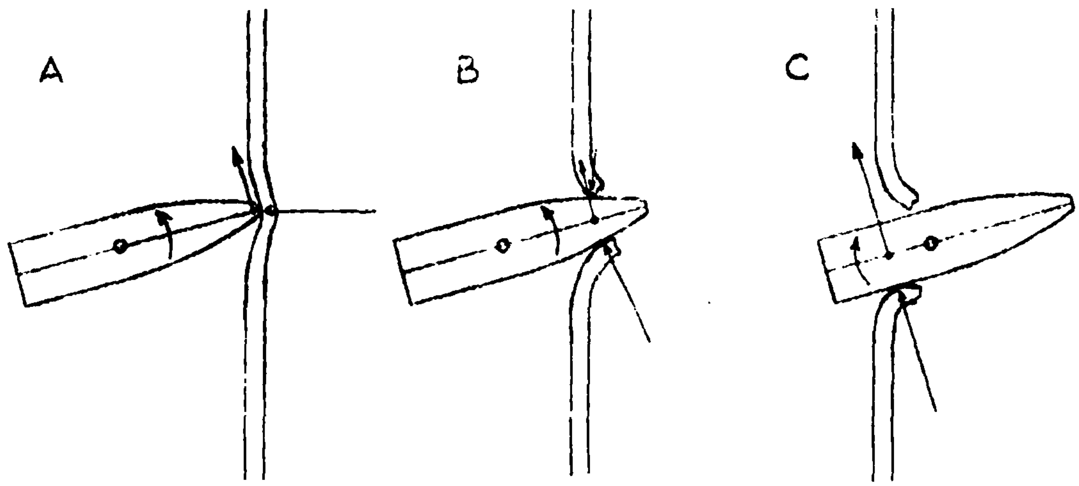
The process of penetration occurring in flexible screens at normal impact may be visualized as follows (see figs. 41, 43, and 44):

As the méplat of the projectile contacts the screen, it starts forming a localized dimple by pushing the sheet ahead of it. It is known that materials have a much greater maximum elongation under impact loads than under static loads. The dural probably behaves in a similar manner to a sheet of rubber during the initial stages. When the projectile has stretched the sheet to the limit of its elongation, rupture of the material starts in two ways. First the material shears in axial planes radiating out from the center of impact thus forming a ring of little pie shaped sections, each one constituting a small cantilever beam supported by the unbroken material. This ring is then bent back by the ogive as the projectile penetrates further and further until the pie sections finally form a crown around the rear of the hole. Probably the shearing and bending take place simultaneously, one augmenting the other.

The significant characteristic about the type of break just described is that the material ruptures in shear and bending. There is relatively little punching action by the méplat and bearing failure of the hole around the sides. The pie sections are given such an impact that they snap out of the way leaving only a narrow band around the inside of the hole showing a Bernelled surface where the material has yielded in pure compression.

How does this type of break influence the resultant yaw? The results showed that the incident yaw had no bearing on the resultant yaw. However, a close correlation was discovered between the incident and resultant orientations, and this correlation gives the clue revealing the mechanism by which the screen produces the tipping. Since the incident and resultant orientations determine the plane of the initial and resultant impulsive couples, a plausible description of the nature of the forces occurring during penetration can be inferred.

The projectile always approaches the screen with a small angle of yaw. When the méplat engages the screen, the reaction creates an overturning couple acting in the plane of orientation as can be seen in the sketches below



Again it should be mentioned that the overturning couple does not displace the projectile but merely imparts an impulsive moment to it. The screen ruptures in shear letting the nose through, and the ogive starts bending back the material around the hole to form the crown. As can be seen (B), the yaw causes one side to be deformed more sharply than the other so that the initial impulsive couple is increased. The couple from the asymetric deformation of the hole diminishes as the center of gravity approaches the plane of the screen. At the instant the resultant force vector passes the center of gravity the couple reverses direction. The tail bears against the side of the hole and creates an impulsive couple which is opposite in direction to the original impulsive couple and thus partially cancels it or in some cases completely overcomes it (see C). If the yaw of the projectile is appreciable, the sheet, being thin, is so deformed by the time the tail contacts the edge of the hole, that the reverse couple cancels only a part of the initial couple. The resultant couple increases the yaw in the plane of orientation and in the direction of the incident yaw.

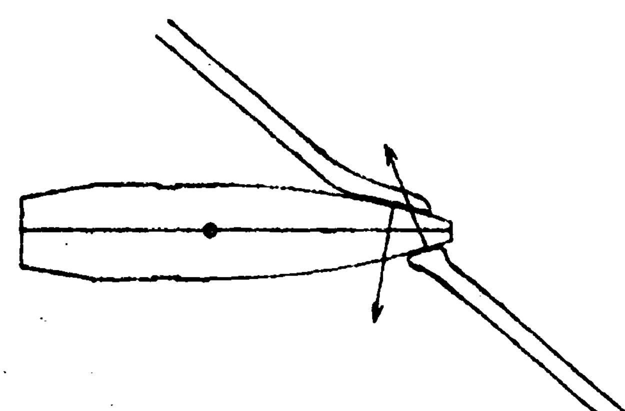
This analysis on first sight might seem to support the original hypothesis concerning the dependence of the resultant yaw on the incident yaw. As the incident yaw increases, the initial upsetting couple is increased. Two factors enter which defeat the initial hypothesis. First, the restoring couple due to the tail increases proportionately to the upsetting couple due to the nose. Consequently, the resultant couple will depend on the balance between the nose and tail effects. Second, the balance will depend on the manner in which the screen ruptures. In other words, the magnitude of the tipping is controlled by the type of rupture occurring for each shot. Now, if the material were perfectly homogeneous, it would always rupture in the same manner and the magnitude of the tipping would be governed by the initial yaw. The fact is that the material is not homogeneous insofar as the way in which it fails is concerned. The type of failure will depend on the microstructure of the metal, and this is governed by microscopic cracks, internal strains due to forming, etc. which may greatly from place to place. Thus the screen may break in an entirely different pattern for two rounds identical in all other respects. So the magnitude of the tipping for the flexible screen class at normal will be in part a random affair varying from round to round, in part determined by the physical properties of the screen.

It must be emphasized that the explanation just given holds only when the incident yaw is small, say less than 10°. Of course, an ordinary small-arms projectile always has a yaw less than 10° in normal flight. The case of large incident yaws is discussed briefly at the end of the section on the "Effect of Angular Velocity."

f. Penetration of Flexible Screens at Angles of Impact.

Continuing with the description of the flexible screen behaviour, a decided change in the whole picture occurs as the angle of impact is increased from zero to an appreciable value.

As the angle of impact is increased from 0° to only 20°, the manner in which the screen resists the penetration of the projectile changes in one fundamental aspect, in that the material around the hole no longer yields in a symmetrical pattern. The spark photographs of the caliber .50 penetrating 1/8" dural at 60° illustrate quite well the nature of the break that takes place at reasonable angles of impact (see fig. 19 to 27). To be specific, assume that the normal to the screen lies in a vertical plane containing the trajectory, that the trajectory is horizontal, and that the projectile strikes the screen on its under side. This is the actual configuration in the spark photographs.



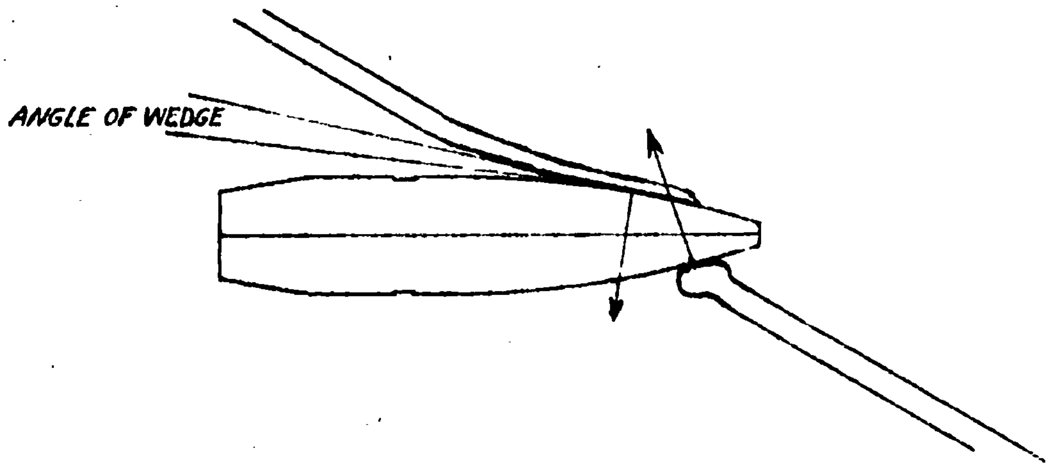
In striking the screen, the upper edge of the méplat digs into the metal (see fig. 20). As penetration starts, the force of the top of the ogival head against the screen is largely perpendicular to the surface. The metal around the top of the hole yields elastically in the beginning forming a long bulge (see figs. 21 and 22). As the projectile penetrates further the nose breaks through and the forcing action of the ogive forms shear cracks along the sides of the bulge, (see fig. 22 and 43). The edge of the bulge breaks up piece by piece but the main body of the bulge bends back as a unit (see fig. 23 to 27 and 43).

The principle component of the force on the bottom of the hole lies in the plane of the screen. The material is well supported in this direction and, as a consequence, it fails largely in compression. The failure is similar to the bearing failure of a rivet. The projectile is subjected to severe localized stresses at this point. A spray of gilding metal from the jacket and dural from the screen can be seen pouring off the lower front edge. This spray is evidence of the violent forming process taking place.

During the passage of the head and fore part of the body, the asymetrical reaction between the screen and projectile subjects the projectile to a couple tending to tip the nose up and tail down. The existence of this couple is inherent in the fact that the sheet is inclined to the direction of motion of the projectile. On the top the resultant force from the bending of the top bulge must act well back along the ogive. Marks of the projectile rubbing along this surface can be seen in every round (see fig. 43). On the bottom of the hole, the force is concentrated in a small region of contact and the material yields largely in compression. The reaction here is so localized that the front edge at the bottom fails in shear at 45° to the surface and splits away.(see fig. 43). The line of action of the force from the bottom intersects the axis of the shell in front of the line of action of the force from the top. Consequently, these forces combine to produce an impulsive couple directed so that the nose is tipped up and the tail down. In other words, a major part of the tipping caused by an inclined flexible screen arises solely from the angle of impact between the screen and the trajectory. Of course, as the center of gravity of the projectile passes the plane of the screen, the tipping couple reverses direction, but by the time the tail reaches the metal, the hole is so completely formed that the tail passes through almost unobstructed and the contribution of the reversed couple is small.

A transition undoubtedly occurs, between the type of break at normal and the type of break at moderate angles of impact, but it must take place before a 20° angle of impact is reached. At 20° the hole shows the characteristic break occurring at large angles of impact. The side inclined towards the trajectory (the top) fails in shear and bending and the side inclined away from the trajectory (the bottom) in bearing.

As the angle of impact is increased beyond 20°, two naturally opposing factors influence the tipping. The force exerted by the bulge at the top of the hole decreases with increase in the angle of impact. This side is ruptured through a process of distortion, shear, and bending caused by a wedging action of the ogival head.



The smaller the angle of the wedge the smaller the force that the projectile is required to exert to fail the screen, and conversely the smaller the reaction this part of the hole can exert to tip the projectile. The bottom of the hole fails largely in bearing and, if the surrounding metal is stiff enough to prevent buckling, it exerts about the same force regardless of the angle of impact. However, if the angle of impact is sufficiently high and the material sufficiently thin and ductile, the lower edge will deform and fail partially in bending. (see fig. 44).

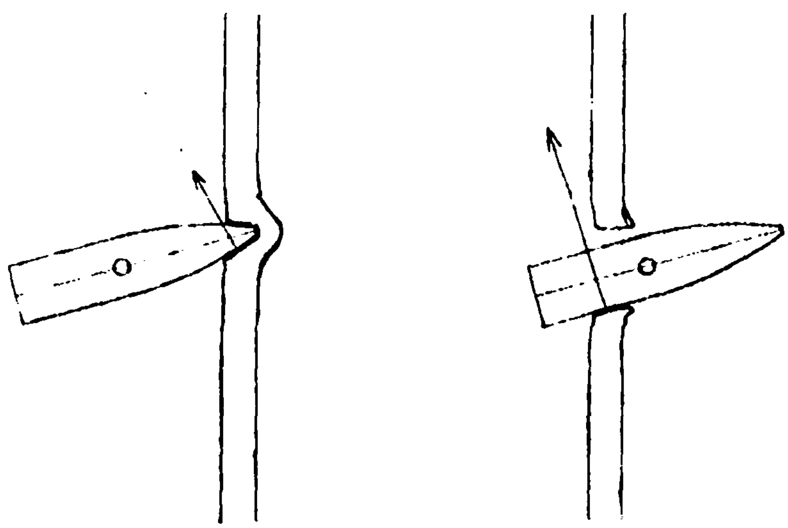
On the other hand, as the angle of impact increases, the lever arm between the lines of action of the forces from the top and bottom edges of the hole increases, and the tipping couple would increase with angle of impact if the forces remained unchanged. However, the forces do not stay unchanged, but may diminish with angle of impact. Consequently, the tipping produced by a screen at an angle of impact is determined by a balance between the reaction forces from the edges of the hole and the length of the lever arm between these forces. If the lever arm increases faster than the resultant force from the top bulge decreases, then the tipping will increase as the angle of impact of a screen is increased. If the reverse holds, the tipping will diminish with increase in angle of impact. Consequently, the tipping may first increase as the screen is inclined from a zero angle of impact to 20° due to the transition from one type of break to another, then diminish as the angle of impact is further increased from 20° to 40° due to the decreased force from the top bulge, and finally increase again on further increase from 40° to 60° due to the rapidly increasing lever arm. (see fig. 70). The exact nature of the course will depend on the material, the projectile, and other physical factors involved.

g. Penetration of Rigid Screens at Normal

The reaction between a tipping screen of the rigid class and the projectile presents an entirely different picture from that just described for flexible screens (see fig. 42). If the thickness of a flexible screen is increased, its inherent static rigidity increases with the third power of the thickness. Assuming that the screen is placed at zero angle of impact, it soon reaches a stiffness at which the bending and shear strength become sufficient to resist a local deformation and failure by bending and shear. When the screen is too stiff to deform in bending the projectile drives its way through by literally pushing the metal to the side and front. The main mass of the metal is so well supported that the hole is formed in a manner similar to the punching action of closely fitting male and female dies. The sides of the hole fail in compression plus shear in concentric rings, and the metal is essentially squeezed out of the projectile's way. A small crown is formed at the rear from the outer layer of dural being pushed to the side.

This type of hole leaves long smooth bearing surfaces on its sides. The sides can exert large transverse forces on the projectile as it passes by them, since the metal resists in pure compression a comparatively large area. A change from the flexible class to the rigid class is shown by the course of the orientation at normal angle of impact. The orientation after penetration is again related to the incident orientation, but instead of being equal, as in the rounds with appreciable yaw in the flexible class, the resultant orientation is 180° opposite the incident (see figs. 46 to 49).

This change of 180° in orientation indicates that the counter-couple due to the tail is the controlling factor for a rigid screen at normal. Since the material fails in compression only and leaves a close fitting hole of considerable depth, it is quite reasonable that the tail couple should be greater than the nose couple. Suppose that the plane of the incident orientation is vertical and the nose of the projectile is inclined up. The head punches its way through, forming the close fitting hole. Due to its incident yaw it is subjected to a couple which tends to tip the projectile in the direction of its incident orientation. As the center of gravity passes through the screen, the tail starts getting caught on the lower edge of the hole. For a flexible screen the material on the bottom was so badly bent by the time the tail reached it that it resisted weakly, but not so for a rigid screen. The material fails in pure compression, and hence will resist deformation by the tail as vigorously as by the head.



On the other hand, by the time the tail reaches the screen the top of the hole has already been enlarged by the head of the projectile, so there is no force exerted by this side to counterbalance the force from the bottom. Consequently the tail gets "pinched", effectively, by the bottom half of the hole. A large impulsive moment is imparted to the projectile through this pinching action. The moment is in a direction opposite to that of the incident orientation, in accordance with the orientation graph. For rigid screens as for flexible, the resultant yaw is independent of the incident yaw. The tipping depends on the balance between the impulsive couples imparted to the nose and tail, and the balance, in turn, depends on the method of rupture of the screen.

The magnitude of the tipping will be in part random, in part determined by the material of the screen and the other physical factors involved. The reaction between the screen and the projectile is much more severe in the rigid class than in the flexible, and the tipping will be proportionately greater. So large is the change, in fact, that a 1/8" dural screen at zero angle of impact produces more tipping than a 1/16" dural screen at 60° angle of impact, the former belonging to the rigid class, the latter to the flexible class, and both having the same projected weight.

The caliber .30 A.P. has a long, straight tail (no boattail). This fact supports further the "tail pinching" theory. Whether a boattail projectile would be subjected to the same "tail pinching" is by no means certain.

h. Penetration of Rigid Screens at Angles of Impact.

As the screen is inclined from normal to moderate angles of impact, the tipping behaves in a manner just opposite to that expected. As the angle of impact is increased from normal, the magnitude of the tipping decreases. In all cases of flexible screens, a rapid increase takes place in the tipping on inclining the screen from normal to 20°. In the case of a rigid screen, on the other hand, the tipping was somewhat less at 20° than at normal, and still less at 40° (see fig. 70).

The decrease in tipping with increase in angle of impact for rigid screens does not appear so mysterious on analysis of the mechanism causing the tipping. In thin screens, the rapid increase in tipping from normal to 20° is due largely to the stiffening of the bottom side of the hole (assuming the same configuration of screen and projectile as before). To review briefly, the stiffening of the bottom occurs as the screen is inclined because the principle force on the bottom side of the hole lies in the plane of the screen and fails the material largely in pure compression. The weakening of the reaction from the top of the hole due to the increased wedging section of the ogive is greatly overbalanced in flexible screens by the stiffening of the bottom as the screen is inclined from normal to moderate angles of impact. In rigid screens, however, the bottom side of the hole is already stiffened at zero angle of impact, since the material fails in compression as previously explained. Consequently, any increase in angle of impact merely weakens the reaction from the top of the hole without strengthening the bottom, and the magnitude of the tipping is reduced.

1. Stripping of Jacket

For both flexible and rigid screens, a stripping of the jacket from the core will take place at some angle of impact if the screen is sufficiently heavy. When the jacket is stripped from the core, the core is tipped violently and the first maximum occurs very close to the screen (see fig. 57 and 69). The tipping process must be modified from that previously outlined for the magnitude of the tipping jumps to a very large value when the jacket is stripped. In many rounds it is not certain that the core has a stable flight beyond the screen. The spin may be greatly reduced and the core may tumble after stripping. Rounds in the stripped condition beyond the screen should be regarded in a class by themselves and this fact should be taken into account in making comparisons with ordinary unmutilated rounds.

4. RESULTS OF TESTS ON INDIVIDUAL SCREENS

a. Introduction

The most important factors determining the behaviour of tipping screens are

(1) The material of the screen.
(2) The thickness of the screen.
(3) The angle of impact.
(4) The caliber of the projectile.

Although these parameters control the performance of all screens, the most critical parameter is the material from which the screen is made. The material will determine the manner in which the screen ruptures during penetration and, hence, other factors being equal, will determine the magnitude of the tipping. The designer will first choose the optimum material for the tipping screen and then select the proper thickness and angle of impact to tip the projectile in question. The results of the present test will be grouped according to the material. The effects of thickness, angle of impact, and caliber of the projectile will be discussed individually in each particular case.

b. Presentation of Results

The data from the yaw cards was plotted as a graph of yaw against distance down range from the tipping screen. The curves for five important and illustrative cases are shown in figs. 50 to 69. Each curve represents one round. Each graph represents a particular configuration, that is, a particular screen at a particular angle of impact fired on by a particular type of projectile.

The armor plate designer is interested in two quantities from the yaw vs distance graphs: (1) the average value of the maximum yaw and (2) the average distance beyond the tipping screen at which the maximum yaw occurs; that is, he needs to know the maximum yaw and the half-period beyond the screen. He will place the armor plate at the half-period distance beyond the screen in order to take full advantage of the tipping. The average value of the maximum yaw was computed and plotted as a function of the angle of impact (see figs. 70 and 72), and as a function of the half-period (see fig. 75).

The average value of the maximum yaw and the average half-period are indicated on the yaw vs distance graphs. The method of indication is complicated by the fact that the period of the yaw is a function of the amplitude. The precise relation is discussed in appendix No. 2. As a first approximation the period near the average maximum yaw varies linearly with the amplitude. If the dispersion is calculated with respect to orthogonal coordinates whose origin is at the position of the mean value, and whose directions are parallel and perpendicular to the half-period - maximum yaw line, the dispersion is a truly random quantity. Probable errors computed in such a coordinate system are representative of a genuine, symmetrical Gausian distribution. The mean value on each graph is indicated by a large cross. The arms of the cross are scale values of the probable errors in the two principle directions. An ellipse surrounding the cross gives the locus of equally probable values.

The calculation giving the slope of the maximum yaw - half period curve proved to be rather lengthy. Furthermore, it is believed that for aircraft armor the caliber .50 projectile is more important than the caliber .30. For these reasons, probable errors were computed for the caliber .50 results only.

The location of the mean values of the yaw and half-period are indicated on the caliber .30 graphs by a small cross in a circle, but the values of the probable error are not given.

c. Tests on 1/16" Duraluminum Screen with Caliber .30 Projectile

The majority of tests on the 1/16" dural were carried out using the caliber .30 projectile. The screen was tested at 0°, 20°, 40°, and 60° angles of impact at both maximum and minimum yaw positions on the undisturbed trajectory. The basic curves for the results at the position of minimum yaw are presented in figs. 50 to 53. The results at the position of maximum yaw are so similar to the results at minimum yaw, that the maximum yaw results are not given. The mean values plotted against angle of impact are shown in fig. 70 and 71. Figure 71 gives the comparison between the results at maximum and minimum yaw positions and demonstrates their similtitude. It is interesting to note that the tipping at minimum yaw is somewhat greater than that at maximum, but, in view of the fact that the difference is less than the probable error, it is not believed to be significant.

The values of the yaw at maximum and minimum positions on the trajectory were averaged from all spark photos taken of the caliber .30 M1922 A.P. projectile. The average maximum yaw (44 rounds) is 4.29° with a probable error of 1.65°. The average minimum yaw (50 rounds) is 1.30° with a probable error of 0.93°. The same averages were computed for the caliber .50 M1 A.P. projectile. The average maximum yaw (50 rounds) is 3.44° with a probable error of 1.24°. The average minimum yaw (29 rounds) is 0.38° with a probable error of 0.13°.

The course of the orientation for the 1/16" dural screen is given in figs. 46 and 47, and photographs of the holes made in the screen are shown in fig. 41.

The results show that the 1/16" dural screen - caliber .30 projectile combination belongs primarily to the flexible screen class. The screen has more rigidity than the 0.0475" steel - caliber .50 combination and hence shows some tendency toward the behaviour of rigid screens. The type of break at 0° angle of impact shows the typical orange peel formation. The course of the orientation is particularly interesting for the combination of the caliber .30 - 1/16" dural screen at normal. The resultant orientation is equal to or rotated 180° from the incident orientation depending on the magnitude of the incident yaw. This is shown in the following table and in figs. 46 and 47.

Round No.	Incident Yaw	Angle between Incident and Resultant Orientation
2	9° 20'	3°
4	6° 10'	15°
5	4° 40'	32°
6	2° 45'	14°
8	5° 40'	5°
53	6° 10'	10°
54	3° 35'	100°
56	5° 5'	11°
7	2° 0'	195°
51	0° 35'	195°
55	0° 35'	215°
60	1° 30'	295°
64	0° 5'	323°
65	1° 25'	243°
66	0° 35'	220°

With a few exceptions, the incident and resultant orientations are equal for large incident yaws and 180° out of phase for small incident yaws. Apparently the nose couple predominates if the yaw is appreciable and the tail couple if the yaw is very small.

It should be noted that the holes are elongated in the direction of the orientation in those cases where the incident yaw was appreciable. This elongation is further evidence that the projectile passes through the screen without any lateral or rotary displacement.

On inclining the screen to an angle of impact of 20°, the average magnitude of the tipping increases sharply from 14.8° to 40.2°. The type of break changes from an orange peel to the typical angle of impact break showing a bulge on top and a bearing failure on the bottom. The course of the orientation becomes more erratic since it is partially controlled by the incident yaw and partially by the angle of impact.

On increasing the screen to 40° angle of impact, the average tipping is reduced somewhat, from 40.2° to 33.8°. The breaks becomes a more pronounced angle of impact type. The course of the orientation is erratic but is influenced more strongly by the screen's inclination than at 20°. The reduction in tipping can be explained by the weakening of the reaction from the top of the bulge on increasing the angle of impact from 20° to 40°, as discussed previously.

On increasing the angle of impact from 40° to 60°, the tipping is increased from 33.8° to 45.7°. The break shows the characteristic shear failure along the sides of the top bulge and the course of the orientation is controlled with a few exceptions by the angle of impact. The increase in tipping on going from 40° to 60° can be accounted for by a greater increase in the lever arm between the forces from the top and bottom of the hole than a decrease in the force from the top. Also, the nose of the projectile shows evidence of being somewhat deformed.

On the basis of these results, the optimum angle of impact for the 1/16" dural screen tipping the caliber .30 projectile is 20°. The tipping at 40° is actually less than at 20°, and the slight increase at 60° hardly justifies the additional projected weight.

d. Unusual Rounds Occurring During Tests on 1/16" Dural Screen

Five unusual rounds occurred during the firings on the 1/16" dural screen with caliber .30. These rounds furnish additional evidence supporting the proposed theory of tipping and deserve a brief discussion (see fig. 45).

At zero angle of impact rounds 2 and 57 had very high resultant yaws, 35° and 43° respectively, compared to an average for the group of 14.8°. The photograph of round 57 was lost, but the photograph of round 2 showed an abnormally high incident yaw of 9.33° (compared to an average of 4.29°). It was first thought that the high incident yaw explained the large tipping, but on plotting the value on the "effect of initial yaw" graph it had the appearance of a wild point. An examination of the holes made by these two rounds revealed the cause of their erratic behaviour. Assuming for conciseness that the plane of orientation is vertical and the nose is inclined up, the photograph shows that a large piece of metal containing the bottom of the hole has broken away. This general failure probably occurred during the initial forcing action of the ogival head. The bottom broke away allowing the tail to pass through largely unobstructed. As the tail met little or no resistance, the normal counter-couple from the reaction of the bottom on the tail was lacking. Consequently, the initial couple due to the head exerted its full influence and drove the projectile to a large resultant yaw.

At 60° angle of impact rounds 30 and 34 had unusually low yaws of 30° and 9°, respectively, compared to an average of 45°. An examination of the hole revealed that the entire bulge on the top of the hole was torn away. Probably the metal ruptured at the base of the bulge during the final stages in its bending letting the projectile through without the normal reaction from top bulge. By the time the head had penetrated far enough to cause a general failure of the top, the force from the bottom was probably past the center of gravity and consequently exerted a counter couple canceling in part the normal couple due to the screen's inclination.

At 60° angle of impact, two rounds, No. 85 and No. 86, were accidentally fired through the same hole. The first round had a normal yaw. The second round had an unusually high yaw. The second round hit just to the side of the first round and must have been subjected to reactive forces on one side only. Since these forces were not counteracted in any way by the open side of the hole, the asymmetrical force distribution produced a large resultant couple and a correspondingly large yaw. This type of behaviour is significant not only because it demonstrates the dependence of the tipping on the type of rupture but also because it shows that a tipping screen would still be effective after considerable firing in actual combat.

It would be rare for the later rounds to strike in exactly the same location as the original rounds, and the later rounds striking close to the first rounds would be given an even greater tipping. Eventually, of course, the screen would become so perforated that it would lose its structural strength.

e. Tests on 1/16" Dural Screen with Cal. .50 Projectile

Eight rounds of caliber .50 were fired at the screen inclined at a 60° angle of impact. The tipping was so small that the test with caliber .50 was not carried out at smaller angles of impact. The results are given by a single point at 60° angle of impact in fig. 72. It is believed that the 1/16" dural screen is too tight to tip the caliber .50 projectile effectively at angles of impact of 60° or less.

f. Tests on 1/8" Duraluminum Screen with Cal. .30 Projectile

The 1/8" duraluminum screen was tested at all angles of impact for both the caliber .30 and the caliber .50 projectiles. In both cases the tests were carried out at the position of minimum yaw on the undisturbed trajectory. The basic curves are given in figs. 54 to 61. The mean values of the tipping plotted against the angle of impact are given in figs. 70 and 72; the course of the orientation is shown in figs. 48 and 49; the pictures of the holes made in the screen are shown in figs. 42 and 43.

The 1/8" duraluminum screen tipping the caliber .30 projectile is an interesting case since this combination is the only representative of the rigid screen class tested. At normal the magnitude of the tipping produced is unusually large, the mean being 58.8°. The orientation course shows a 180° reversal in orientation from entrance to exit in all rounds. The hole made in the screen has smooth walls except for a small crown at the back and there are scoring marks on the walls made by the engraving on the side of the projectile. The hole has the appearance of having been drilled. Even in the case of this rigid screen the hole is elongated in the direction of the orientation for those rounds having a high incident yaw. This evidence further supports the statement that the reaction between screen and projectile is entirely impulsive.

On inclining the screen to a 20° angle of impact the tipping is reduced, and on further inclining the screen to 40° the tipping remains the same as at 20°. The course of the orientation at 20° and 40° shows that the incident orientation is still the predominant factor. The type of break is a compromise between the punched hole at normal and the typical type of failure occurring at angles of impact. The top of the hole yields partially by bending a bulge back and partially by disintegrating the metal around the hole. The reduction in tipping is due to a weakening of the top side of the hole as previously discussed.

The projectile was deformed to a noticeable extent by the 1/8" screen at 40°. The jacket over the nose of the core was pushed back and bent to the side. In fact, one round out of seven had the jacket stripped completely off. This deformation might compensate partially for the reduced resultant yaw. As stated previously the deformation makes the determination of the yaw from the major axis of the hole in the yaw card somewhat uncertain. The accuracy of the results at 40° is therefore less than that of the other configurations.

On increasing the angle of impact from 40° to 60°, the resistance of the screen is sufficient to strip the jacket from the core. The break in the metal gives an appearance of a violent disintegration of the region adjacent to the hole rather than a smooth punching action. The core is tipped to a very great yaw a short distance beyond the screen (see fig. 57). A comparison between the stripped and normal rounds is hardly justified in view of the radical change in the physical characteristics of the projectile. For this reason the course of the orientation is not given.

The optimum angle of impact for the 1/8" dural screen is normal if only 20° and 40° are considered. The tipping produced at 60° is greater than at normal and the rounds are stripped. Whether these two factors would justify the increased projected weight can only be determined by firing on actual tipping screen - armor plate combinations.

g. Remarks on Stripped Rounds

Tipping screens that are sufficiently heavy to strip the jacket may justify their additional weight in certain cases. The physical properties of the projectile and the character of its flight are altered radically on stripping. The stability of its motion appeared to be materially reduced. Its yaw increased very rapidly to extreme values shortly beyond the screen. If the core was still stable, it started a quick oscillation in yaw of great amplitude. In some rounds the amplitude increased from one period to the next indicating a dynamic instability. In others the core appeared to be tumbling (see figs. 57 and 69). Both the caliber .30 and caliber .50 cores were tipped to an amplitude of greater than 30° within a foot of the tipping screen. For certain military applications, the reduction in the necessary distance between the tipping screen and the armor plate may be the determining factor in the design of the screens.

h. Comparison of 1/16" and 1/8" Dural Screens

It is not strictly proper to compare the results of the caliber .30 firings on 1/16" and 1/8" dural screens since the two screens are categorically different. Nevertheless a comparison has been made by taking the difference between the average resultant yaws produced by the two screens at a given angle of impact and plotting this difference against the angle of impact (see fig. 73). The large value at normal comes from the change from a flexible to a rigid class. The difference drops at 20° to less than half that at 0°, but increases beyond 20°. The advantage secured by a screen of the rigid class at normal is immediately apparent. It should be noted, however, that in all cases an increase in the thickness produces a greater magnitude of tipping.

The 1/16" dural at 60° angle of impact has the same projected weight as the 1/8" dural at normal. For the caliber .30 projectile the 1/8" dural at normal is superior since it produces 13° more tipping than the 1/16" at 60°. In a way this is fortunate since it is simpler to construct an airplane with a flat transverse bulk head of 1/8" dural than an inclined bulk head of 1/16" dural at 60°. On the other hand, the 1/16" dural produces almost as much tipping at 20° as at 60°. The selection must be based on firings made on a prototype armor installation. For the caliber .50 projectile, the comparison between 1/16" dural at 60° and 1/8" dural at normal is just opposite to that of the caliber .30. The 1/16" dural at 60° produces 14.3° more tipping than the 1/8" dural at normal. The conflict in the results for the two calibers is caused by the change in class from flexible to rigid for the caliber .30 projectile on going from a 1/16" dural to a 1/8" dural screen.

i. Tests on 1/8" Dural Screens with Caliber .50 Projectiles

The 1/8" dural screen tipping the caliber .50 projectile belongs to the flexible class. The magnitude of the tipping increases with increase in angle of impact, starting at a very low value at normal, increasing rapidly from 0° to 20° and more gradually from 20° to 60°. The magnitude of the yaw beyond the tipping screen at normal angle of impact was so small that it was not possible to measure accurately the course of the orientation beyond the screen. Consequently, the course of the orientation through the screen is given for 20°, 40°, and 60° only. The angle of impact is clearly the controlling factor. The type of break is typical of a flexible screen.

A close similarity might be expected between the 1/16" dural tipping the caliber .30 and the 1/8" dural tipping the caliber .50 since the caliber -weight ratio is nearly the same for the two. If anything, the 1/8" dural screen compared to the 1/16" dural screen is heavier than the caliber .50 projectile compared to the caliber .30. Consequently, one would expect the 1/8" dural screen to produce a greater tipping of the caliber .50 projectile than the 1/16" dural of the caliber .30. Actually, however, the opposite should be true. If it is assumed that the tipping is proportional to the weight of metal displaced and that an analysis can be made using the theory of small oscillations, the 1/8" dural screen should produce less tipping of the caliber .50 than the 1/16" dural of the caliber .30. The theory is discussed in detail in appendix 3. The results are shown in fig. 74. The hypothesis holds from zero angle of impact up to 20°. Beyond 20° the curves reverse and the 1/8" screen produces more tipping of the caliber .50. Probably the assumption that the tipping is proportional to the weight of metal displaced is not valid at appreciable angles of impact.

The 1/8" dural screen is an important case because it is the lightest dural screen that produced an effective tipping of the caliber .50. The 1/16" dural screen was sufficiently heavy to tip the caliber .30 effectively but not the caliber .50. The general statement may be made that a screen that is heavy enough to tip effectively a certain caliber will be heavy enough to tip smaller calibers but may or may not produce sufficient tipping of greater calibers.

The proper complement to the 1/8" dural screen-caliber .50 test would have been a dural screen sufficiently thick to belong to the rigid class in tipping the caliber .50 projectile. Due to the gain in simplicity of construction by using a normal screen, a knowledge of the minimum thickness necessary to change the screen from flexible to rigid classification would be an important contribution. The original program called for tests on 1/4" dural screens. Unfortunately, the Air Corps failed to obtain this material for the Proving Ground, and this part of the original program had to be omitted. Until such a test is carried out, no comparison of the 1/8" dural screen - caliber .50 projectile combination can be made on the basis of projected weight.

i. Tests on Weak Materials: Soft Aluminum, Copper, and Brass.

Before the test was started, the physical characteristics of a material that would best suit it for tipping screen use were not established and consequently materials were chosen which would cover the field most completely. It was believed that the tensile and shear strengths and the strength weight ratio were important properties. The aluminum, copper, and brass represent materials having a low tensile strength. The aluminum has a low weight per unit area, the same as the duraluminum.

The copper and brass have high weights per unit area, a little greater than steel. Also, the aluminum and the copper have a high ductility. The brass has the greatest tensile strength of the three.

The three materials were tested at 60° angle of impact using the caliber .50 projectile, and the copper and brass were also tested at zero angle of impact (see fig. 72). The results at 60° angle of impact showed a decided inferiority in performance on an equal weight basis to both the dural and the steel and the tests were not carried out at 20° and 40°. The 1/8" aluminum was inferior to even the 1/16" duraluminum. The 1/8" copper gave only 2/3 the tipping produced by the 0.0951" steel; the 1/8" brass gave about the same tipping as the 0.0951" steel. Since both the brass and the copper are considerably heavier per unit area than the steel, their performance demonstrates that they are inferior materials for tipping screen use.

The fact that materials having a low tensile strength produce less tipping than materials having a high tensile strength agrees with the proposed mechanism by which the tipping screen operates. One photograph was taken of the hole made in the soft aluminum at 60° by a caliber .50 to illustrate the type of rupture occurring in a weak, ductile material (see fig. 45). The top of the hole bulges but the material is so ductile that it is formed more or less plastically by the passage of the ogival head. The bottom of the hole also yields plastically as evidenced by the large lip at the front. The reactive forces are small due to the ease with which the material in the screen is displaced and the tipping is correspondingly small.

The 1/16" and 1/8" durals were the only materials tested with both caliber .30 and caliber .50 projectiles. The dural results form a basis for comparing the .30 and .50 caliber projectiles. Adequate protection should be maintained against both calibers. Since a screen adequate for tipping caliber .50 projectile will be more than adequate for tipping caliber .30 projectiles, all subsequent tests were carried out with the caliber .50 projectile only.

k. <u>Tests on .0475" and .0951" Mild Steel Screens</u>

The mild steel tipping screens were tested with the caliber .50 projectile only. Both thicknesses belonged to the flexible class. The 0.0475" steel screen is a particularly representative example of this class. The metal has both a reasonably high tensile strength and a high ductility. The "orange peel" formation at zero and the angle of attack effect can be seen clearly and distinctly (see fig. 44). The variation in the tipping produced by both steel screens with angle of impact is similar to that of the 1/8" dural screen (see figs. 62 to 69 and 72). The magnitude of the tipping increases as the angle of impact increases from normal up to 40°. Beyond 40° the two screens deviate from the course of the dural curve. The 0.0475 steel screen produces less tipping as the angle of impact is increased beyond 40°. The photograph of the hole made at 60° discloses the reason for the decrease. The inclination of the screen has become so great that the bottom part of the hole yields in bending and shear as well as the top. Consequently, the reactive force from the bottom is decreased and the tipping is correspondingly less. On the other hand the 0.0951" steel screen has sufficient strength at 60° angle of impact to strip the majority of rounds and the tipping is greatly increased.

The effect of thickness appears unobscured by a change in regime since both screens belong to the flexible class. The difference between the average maximum yaws of the .0951" and .0475" steel screens is plotted against the angle of impact in fig. 73. The difference increases gradually with angle of impact. Beyond 40° the difference becomes abnormally large since the fundamental behavior of the screens changes. At normal the yaws are so small that the difference could not be accurately measured. Between these two limits, the increase in thickness produces a constant proportional-increase in tipping. At 20° the increase is 26.1%; at 40° the increase is 28.2%. The theory of small oscillations would predict a 100% increase in tipping if the thickness were doubled. However, it is doubtful whether this theory can be applied strictly either for yaws as large as 35° or at moderate angles of impact.

It is instructive to compare the curve giving the effect of the thickness for the .0475" and 0.0951" steels and the curve for the 1/16" and 1/8" durals (caliber .50 and .30 respectively). The steel screens both belong to the flexible class, so increasing the thickness brings about a uniform relative increase in tipping over most of the range. The dural screens belong to different classes, so increasing the thickness causes a change in regime from flexible to rigid with a great increase in tipping at normal and a proportionately smaller increase at moderate angles of impact. If the results from the two screens were compared blindly without taking into account the change from a flexible to a rigid class in the case of the dural, the effect of thickness would be obscure and appear arbitrary and conflicting.

The steel compares favorably with the duraluminum as a satisfactory material for tipping screens. The 0.0475" steel has practically the same weight per unit area as the 1/8" dural and the two can be compared directly (see fig. 72). The steel produces a little less tipping than the dural at all angles of impact. A tabular comparison of the two is as follows:

Angle of Impact	$\bar{\delta}_M$ Dural	$\bar{\delta}_M$ Steel	Difference
0°	5.6°	3.2°	2.4°
20°	34.8°	29.8°	5.0°
40°	44.6°	37.0°	7.6°
60°	49.8°	34.0°	15.8°

At 20° and 40° the difference is not great, only about 20%, and the advantages in supply and cost of the steel may well outweigh the disadvantage in tipping. Of course, the .0951" steel has double the weight per unit area of the dural and produces less than 10% increase in tipping (except at 60°). On the other hand, the 0.0951" steel inclined at 60° strips the jacket from the projectile. The core yaws rapidly to an amplitude of 68.1° in only 3.3 feet beyond the screen. The reduction in spacing between the tipping screen and the armor plate may justify the added weight in certain cases.

The steel used in tho present test was a ductile, cold rolled steel and had a comparatively low tensile strength. Increasing the tensile strength may increase the tipping produced by a thin steel screen sufficiently so that the steel may become the equal or the superior of the dural. A steel having a tensile strength of 210,000 lbs/sq.in. would be required. Due to inability to obtain high tensile steels of the proper thickness, this phase of the investigation had to be discontinued.

The dural possesses certain advantages due to its low density that may make it superior to steel even though the two have the same strength-weight ratio. The added thickness of the dural supports the bottom of the hole and prevents it from failing partially in bending. Furthermore, the bending strength of the top of the hole is greater for dural than for steel of the same strength-weight ratio. This assertion is discussed in appendix 4. The analysis shows that, for steel and dural sheets having the same weight per unit area, the dural will exert 3 times the force on the projectile that the steel will exert as the head of the projectile wedges the bulge on the top of the hole out of its way.

One sample of Czechoslovakian helmet armor was tested at 60° angle of impact with both caliber .30 and caliber .50 projectiles. The results are plotted as a single point on the graph giving the effect of the angle of impact (see fig. 70 and 72). Little was known about the properties of the steel. It was described as a high manganese steel, but the manganese content could not have been very large since the sample was definitely magnetic. Its tipping qualities were poor. It produced about the same tipping of the caliber .30 as the 1/16" dural, but its weight per unit area was 1.82 times that of the 1/16" dural. It produced less than half the tipping of the 0.0475" mild steel although its weight and thickness are the same. The reasons for the decided inferiority of the Czechoslovakian helmet armor are not clear. The material appears to be quite brittle from the appearance of the hole and the lack of ductility may be a contributing factor. However, its performance will remain a mystery until more is known about its physical properties.

1. Splash Tests:

One important characteristic of tipping screens has been omitted from the discussion so far. As the projectile breaks its way through the screen, small pieces of the screen are broken loose and driven to the rear with velocities comparable to that of the projectile. The conglomerate of these small pieces is called the splash. It can be seen clearly in the photographs of the caliber .50 penetrating the 1/8" dural screen at 60° angle of impact (see fig. 19 to 27). Since the splash has a high velocity, it can do considerable damage by itself. Furthermore its angle of spread is very wide and it may hit parts that otherwise would be adequately protected. In order to measure the amount of splash a yaw card was placed in a plane parallel to the tipping screen one inch behind it. Both the projectile and the splash punched holes in the card. The importance of the splash was recognized rather late in the course of the investigation and the data is somewhat incomplete. Records were taken of the splash from the caliber .50 projectile penetrating the 0.0951" steel screen at 0°, 20°, 40°, and 60° angles of impact and the 0.0475" steel, 0.0625", and 0.125" dural screens at a 60° angle of impact. The splash cards are shown in figs. 29 to 32 reduced in size. They are all reduced the same amount, however, and the scale can be determined by looking at the record made by the 0.0951" steel screen at 0° angle of impact. The caliber .50 projectile has left a clean, sharp hole whose exact circular border can be seen marked on the card around the torn-out center. As the angle of impact is increased, the splash is increased. At 60° the 0.0951" steel screen strips the jacket and the splash becomes very severe. The thicker the metal, the greater the splash, as can be seen by comparing 1/16" dural with 1/8" dural. Weight for weight the steel has less splash than the dural (the 0.0475" steel and the 0.125 dural have the same weight per unit area), but the steel produces less tipping than the dural. If the thickness or the tensile strength of the steel are increased sufficiently to equal the tipping produced by the dural, it is not possible to say from the results at hand which material would give the greater splash.

CONCLUSIONS

A relatively light screen will impart a sufficient torque to a projectile penetrating the screen to tip the projectile to a considerable angle of yaw a half-period beyond the screen. The torque is purely impulsive in nature. It gives the projectile an increase in kinetic energy without any actual displacement during penetration. The increase in kinetic energy drives the projectile to a large yaw a half-period beyond the screen. The half-period is dependent on the magnitude of the resultant yaw. The larger the resultant yaw the shorter the half-period.

In certain cases, the screen will strip the jacket off the core. The core is tipped to a very large yaw a short distance behind the screen.

In general, a screen that is strong enough to tip a certain projectile sufficiently will be more than strong enough to tip a lighter projectile but may or may not be strong enough to tip a heavier projectile. The distance between the screen and the maximum resultant yaw will depend on the caliber, the condition of the projectile beyond the screen, and the severity of the tipping.

The mechanism by which tipping is produced by the screen depends on the properties of the material and its angle of impact. Screens can be classified in general as "flexible" or "rigid". The behaviour of the two is basically different.

The magnitude of the resultant yaw is independent of the incident yaw and angular velocity as long as the incident yaw is small (less than 10°). It is determined for a particular configuration by the manner in which the material ruptures during penetration.

The physical properties of a material that will best suit it for tipping screen use are high tensile and shear strengths and a high strength-weight ratio. The optimum material of those tested was duraluminum. Mild steel of the same weight produced about 30% of the tipping produced by the dural. The performance of high tensile strength steels was not investigated due to lack of material. ?

The angle of impact and the thickness should be considered together since the projected weight is the critical factor for airplane design. The effect of thickness is complicated by the radical change in behaviour encountered if an increase in thickness changes the screen from the flexible class to the rigid class. The variation in the tipping with angle of impact depends on the thickness, the material, and the caliber of projectile in a manner so complex that a comprehensive investigation of the entire range of thickness and angles of impact will be necessary before any general conclusions can be drawn.

In all cases, an increase in thickness brought about an increase in tipping. The same cannot be said for an increase in angle of impact. An increase in angle of impact may increase or decrease the tipping depending on the particular configuration. The effect of the angle of impact should be investigated for each individual case.

The optimum screen can be selected on a basis of projected weight in three isolated cases. For the caliber .30 projectile a 1/8" dural screen placed at 0° angle of impact produces more tipping than a 1/16" dural screen placed at 60° angle of impact. For the caliber .50 projectile a 0.0475" mild steel screen placed at 60° angle of impact produces much more tipping than a 0.0951" mild steel screen placed at 0° angle of impact; also, the 1/16" dural screen placed at 60° angle of impact produces more tipping than 1/8" dural screen placed at normal. It should be noted that the results for the first case conflicts with the last two.

The splash produced by a screen depends on the material, the thickness, and the angle of impact. The amount of splash increases with both thickness and angle of impact. Weight for weight, a mild steel screen gives less splash than a dural screen. There is not sufficient data from the present investigation to compare the splash of the two metals if the thickness or the tensile strength of the steel were increased sufficiently to give the same tipping as the dural.

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APPENDIX 1

Relation Between Maximum Yaw and Angular Velocity at Minimum Yaw

The resultant angular velocity of the projectile is given by the equation (see ref. 8).

$$\omega = \sqrt{\mathring{\delta}^2 + \mathring{\varphi}^2 \delta^2}$$

where

ω = Resultant angular velocity

δ = Angle of yaw

φ = Angle of Orientation

Assume that the minimum yaw is very small. Then δ is given by the equation

$$\delta = \alpha \sin \frac{pt}{2}$$

$$\mathring{\delta} = \frac{p\alpha}{2} \cos \frac{pt}{2}$$

where α = amplitude of the maximum yaw

$$p = \Omega \sqrt{1 - \frac{1}{s}}$$

(see appendix 2 for symbolism)

Assume that $\mathring{\varphi}$ can be approximated by its steady value

$$\mathring{\varphi} = \frac{1}{2}\,\Omega$$

Then

$$\omega^2 = \frac{\Omega^2 \alpha^2}{4} \left\{1 - \frac{1}{s} \cos^2 \frac{pt}{2}\right\} .$$

At minimum yaw $\cos^2 \frac{pt}{2} = 1$.

$$\therefore \quad \omega = \left(\frac{D}{2}\sqrt{1 - \frac{1}{s}}\right) \alpha$$

or

$$\omega = \text{const} \times \alpha$$

Consequently the angular velocity at minimum yaw is proportional to the amplitude of the maximum yaw.

APPENDIX 2

Relation between the Semi-Period and the Maximum Yaw

Hitchcock gives the following formulae for the relation between the semi-period and the maximum yaw. (see ref. 1)

$$\frac{\Omega T}{2\pi} = \frac{K}{\sqrt{\frac{2}{1+w_1} - \sigma}}$$

where

$$\Omega = AN/B$$

A = Axial Moment of Inertia

B = Transverse Moment of Inertia

N = Spin in radians per second.

T = Period.

w_1 = cosine of the maximum yaw

σ = Moulton's Stability factor = $\frac{1}{s}$

$$K = (1 + \kappa)\left(1 + \frac{\kappa^2}{4} + \frac{9\kappa^4}{64} + \ldots\right)$$

$$\kappa = \frac{\sqrt{c}-1}{\sqrt{c}+1}$$

$$c = 1 + \frac{1 - w_1}{2(s-1)}.$$

The formulae is based on the assumption that the minimum yaw is zero. This assumption is not correct in the present case but the error introduced in this way will be small.

At the maximum yaw the rate of change of orientation, φ', is given by the equation

$$\varphi_1' = \frac{\Omega}{2}$$

where φ_T' is given in radians per second.

$$T \frac{\varphi_T'}{\pi} = \frac{K}{\sqrt{\frac{2}{1+w_1} - \sigma}}$$

if φ_L' is given in radians per foot,

then

$$\varphi_T' = \varphi_L' \times V$$

where

V = Velocity of the Projectile

$\sigma = 1/s$

where

s = Conventional Stability Factor.

but $TV = L$ = Period in feet

$$\frac{\varphi_L' L}{\pi} = \frac{K}{\sqrt{\frac{2}{1+w_1} - \frac{1}{s}}} .$$

Hitchcock has computed $\frac{L\varphi'}{\pi}$ as a function of w_1 and S (see ref. 7). φ', L, and w_1 were experimentally determined. In order to compare the theory with the experiments, L was plotted as a function of w_1 first from the values measured from the experimental results and second from values of L computed from the formulae using measured values of w_1 and φ_L' (see fig. 75). Each point represents the average of a group of rounds. The symbols with tails represent the measured values of L and those without tails the computed values of L. As can be seen the two curves have the same character but differ somewhat at large values of the maximum yaw. The curves are brought into coincidence at a point whose yaw was measured from the yaw cards and whose semi-period was computed from the measured yaw and rate of change of orientation. The yaw cards were not placed further than 10 feet beyond the tipping screen, and, since the semiperiod is around 12', L could not be measured directly for small yaws. However, measurements of the yaw were made at the 12.3 ft. position from the muzzle during the angular velocity investigation (see the section on the Effect of Angular Velocity). Assuming that 12.3 ft. is the correct semiperiod for the first maximum yaw, the average of the yaws measured at this distance is shown on the graph by a + symbol. The correct value probably lies somewhere between these two points.

The slopes of the experimental and semi-empirical $\bar{h}$ vs $\bar{\delta}_m$ curves were measured graphically and plotted against the value of the maximum yaw (see fig. 76).

The average maximum yaw for any particular group of shots was used to determine the slope of the semiperiod - maximum yaw curve from this graph. The experimental values of the slope were used.

APPENDIX 3

Comparison of Tipping Produced by the 1/16" Dural Screen on the Caliber .30 Projectile and by the 1/8" Dural Screen on the Caliber .50 Projectile

If the course of the yaw can be represented by a simple trigonometric function of the time and the angular velocity due to the rate of change of orientation can be neglected

$$\delta = \alpha \sin(\frac{pt}{2})$$

then the theory of small oscillations says that the

$$\text{Kinetic Energy (at } \delta = 0) = \frac{1}{2} B \overset{\circ}{\delta}{}^2$$

and the

$$\text{Potential Energy at } (\delta = \alpha) = \frac{B}{8} p^2 \alpha^2$$

and that the

$$\text{Kinetic Energy (at } \delta = 0) = \text{Potential Energy(at } \delta = \alpha)$$

that is

$$\frac{1}{2} B \overset{\circ}{\delta}{}^2 = \frac{B}{8} p^2 \alpha^2$$

where

δ = angle of yaw

B = transverse moment of inertia

p = time scale factor

α = amplitude of the maximum yaw.

When the projectile penetrates the tipping screen it is subjected to an impulsive couple of magnitude

$$m = \int \text{Torque x dt} = \text{Ave. Torque x } \Delta t.$$

According to Newton's laws of motion:

Change in angular momentum = impulsive torque.

Neglecting the oscillation in yaw present before striking the screen and assuming that the entire oscillation in yaw is started by the impulsive couple from the tipping screen:

$$\text{Change in angular momentum} = B\dot{\theta} = m.$$

$$\therefore \quad \dot{\theta} = m/B$$

and

$$\frac{1}{2} B\left(\frac{m}{B}\right)^2 = B\,\frac{p^2\alpha^2}{8}$$

$$\therefore \quad \alpha = \frac{2m}{Bp} .$$

Now

$$p = \frac{AN}{B} \times \sqrt{1 - 1/s} . \qquad \text{(see ref. 8)}$$

Where

A = Axial Moment of Inertia

N = Spin in Radians/second.

s = Stability Factor

$$\therefore \quad \alpha = \frac{2m}{AN\sqrt{1-1/s}}$$

and

$$\frac{\alpha_{50}}{\alpha_{30}} = \left(\frac{m_{50}}{m_{30}}\right) \times \frac{A_{30}N_{30}\sqrt{1-1/s_{30}}}{A_{50}N_{50}\sqrt{1-1/s_{50}}} .$$

where

$( )_{30}$ = Quantity for the Caliber .30

$( )_{50}$ = Quantity of the Caliber .50

According to the initial assumption

m = Constant x Area of the Hole x Thickness of the tipping screen

$$\therefore \quad m = kd^2t$$

where

k = constant

d = caliber of the projectile

t = thickness of the tipping screen.

$$\therefore \quad \frac{\alpha_{50}}{\alpha_{30}} = \frac{d^2_{50}}{d^2_{30}} \times \frac{t_{50}}{t_{30}} \times \frac{A_{30}\, N_{30} \sqrt{1 - 1/s_{30}}}{A_{50}\, N_{50} \sqrt{1 - 1/s_{50}}}$$

Now

d_{50} = 0.5 inch

d_{30} = 0.3 inch

t_{50} = 0.125 inch

t_{30} = 0.0625 inch

A_{50} = 21.45 grain inches^2

A_{30} = 1.806 grain inches^2

N_{50} = 14,070 radians/sec

N_{30} = 19,600 radians/sec

s_{50} = 1.67

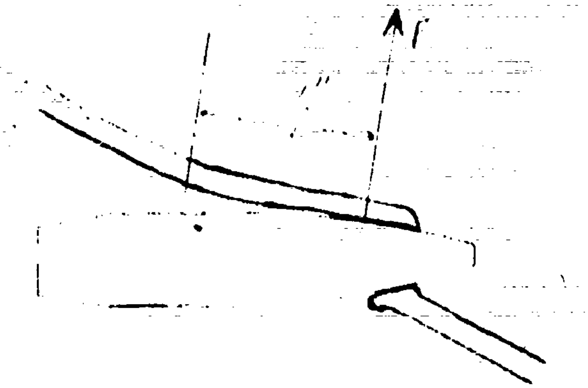
s_{30} = 1.47

$$\therefore \quad \frac{\alpha_{50}}{\alpha_{30}} = 0.58$$

According to assumptions made above, the 1/8" dural screen should produce only 0.58 the tipping of the caliber .50 as the 1/16" dural screen of the caliber .30.

APPENDIX 4

Comparison between Steel and Dural Tipping Screens Having the Same Strength-Weight Ratio.



Assume that the top bulge can be represented by a small cantelever beam. The beam will have the same dimensions for both the steel and the dural screens except for its thickness. For the sake of conciseness, assume that the density and strength-weight ratio are the same for the dural and the steel and both equal to 3.

then

$$t_s = \frac{1}{3} t_a,$$

$$f_s = 3 f_a$$

$$\tau_s = 3 \tau_a$$

where t_s = thickness of the steel sheet

t_a = thickness of the dural sheet

f_s = ultimate tensile strength per unit area of the steel

f_a = ultimate tensile strength per unit area of the dural

τ_s = ultimate shear strength per unit area of the steel

τ_a = ultimate shear strength per unit area of the dural.

The force required to rupture the material in shear initially will be the same for the two materials, since:

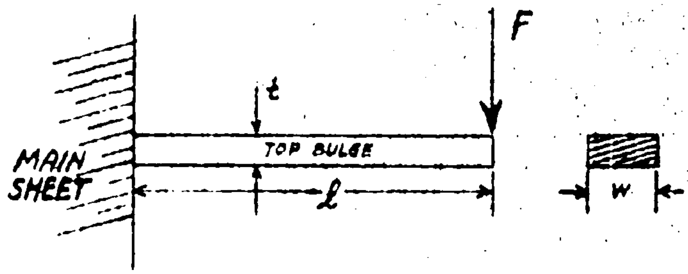
Force to shear one side of pie section =

$$\ell t \tau = \ell t_s \tau_s = \ell \frac{t_a}{3} \times 3 \tau_a = \ell t_a \tau_a .$$

But the force required to bend the top bulge back is different for the two materials:

On the assumption that the bulge is a small cantilever beam, once shear has taken place, the equation of equilibrium is

$$F\ell = M = fS$$



where

F = Force Reaction with the Projectile.

M = moment required to bend the beam.

f = ultimate tensile strength of the outside fibre.

S = section modulus.

ℓ = length of the beam.

Assume that the average section modulus can be represented by a rectangular area, w wide and t thick. Since the bulges are the same size in the steel and dural, w and ℓ will be constant.

Then

$$S = \frac{wt^2}{6}$$

So

$$M = f\,\frac{wt^2}{6} = F\ell$$

$$\therefore \quad F_a = \frac{wf_a t_a^{\,2}}{6\ell}$$

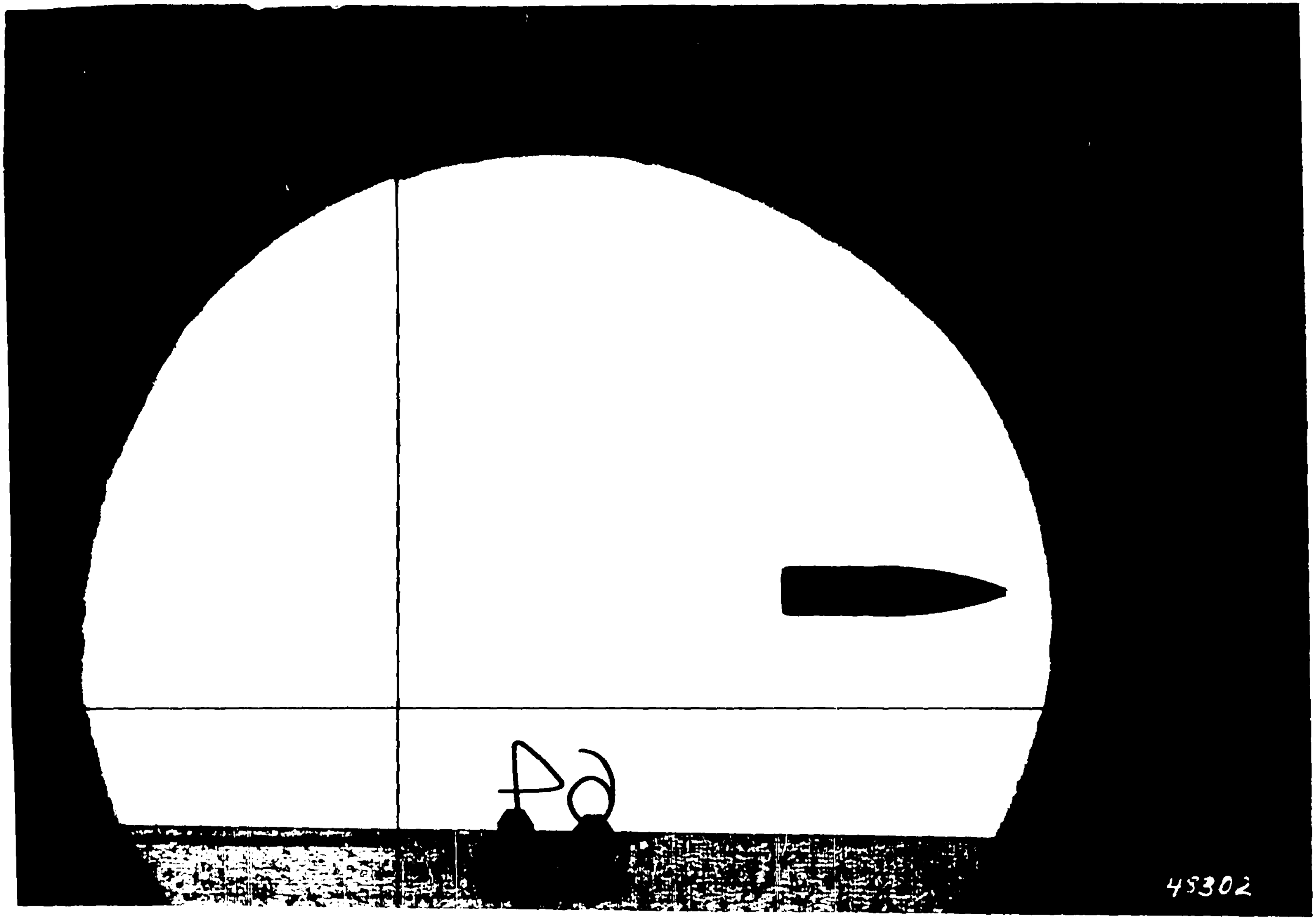
$$F_s = \frac{wf_s t_s^{\,2}}{6\ell}$$

and

$$\frac{F_a}{F_s} = \frac{f_a}{f_s} \times \left(\frac{t_a}{t_s}\right)^2 = \left(\frac{1}{3}\right)\left(\frac{3}{1}\right)^2 = 3.$$

$$\therefore \quad F_a = 3F_s \;.$$

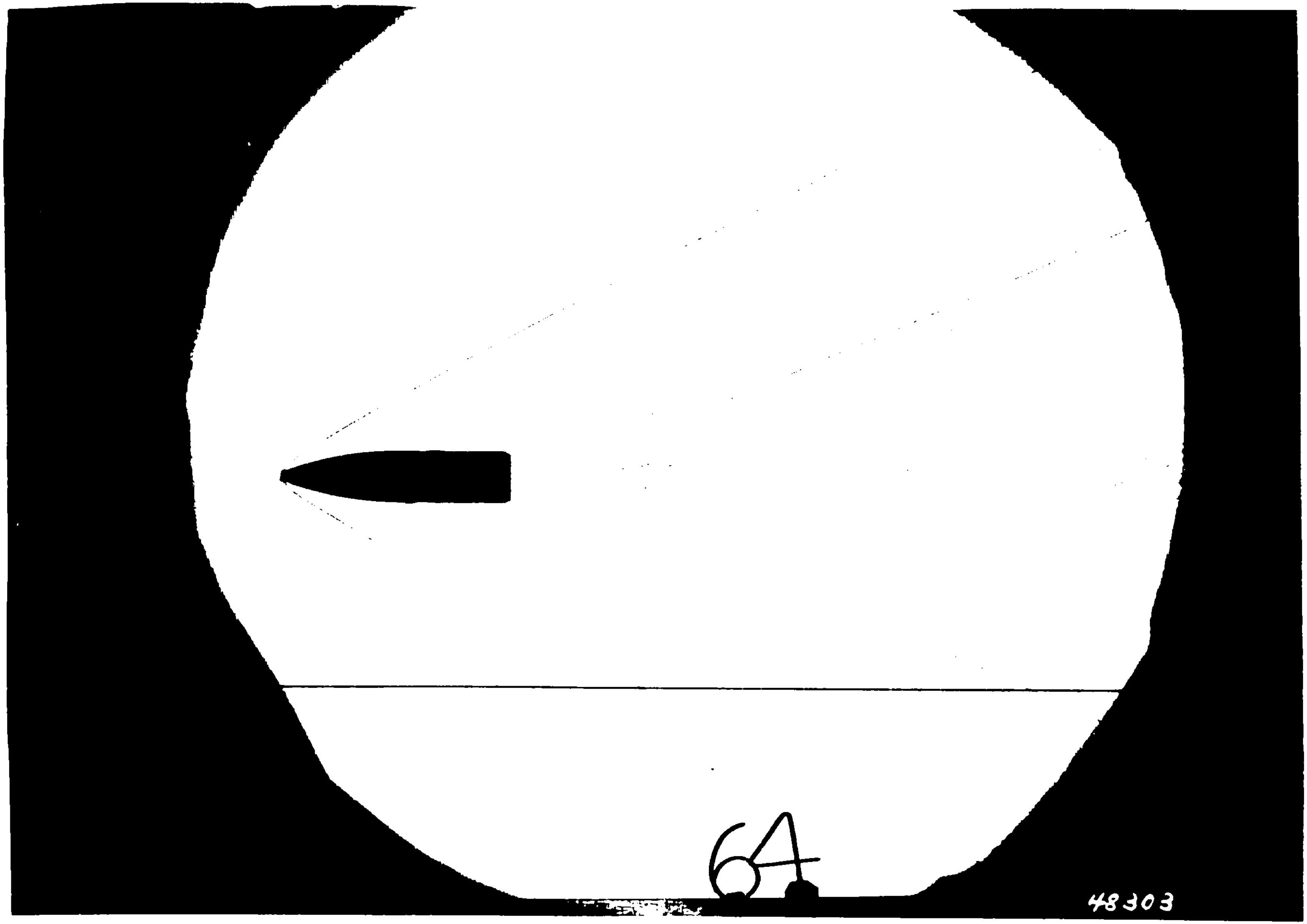
Figure 13



Projectile, Caliber .30 M1922 At Service Velocity
Projection on Vertical Film

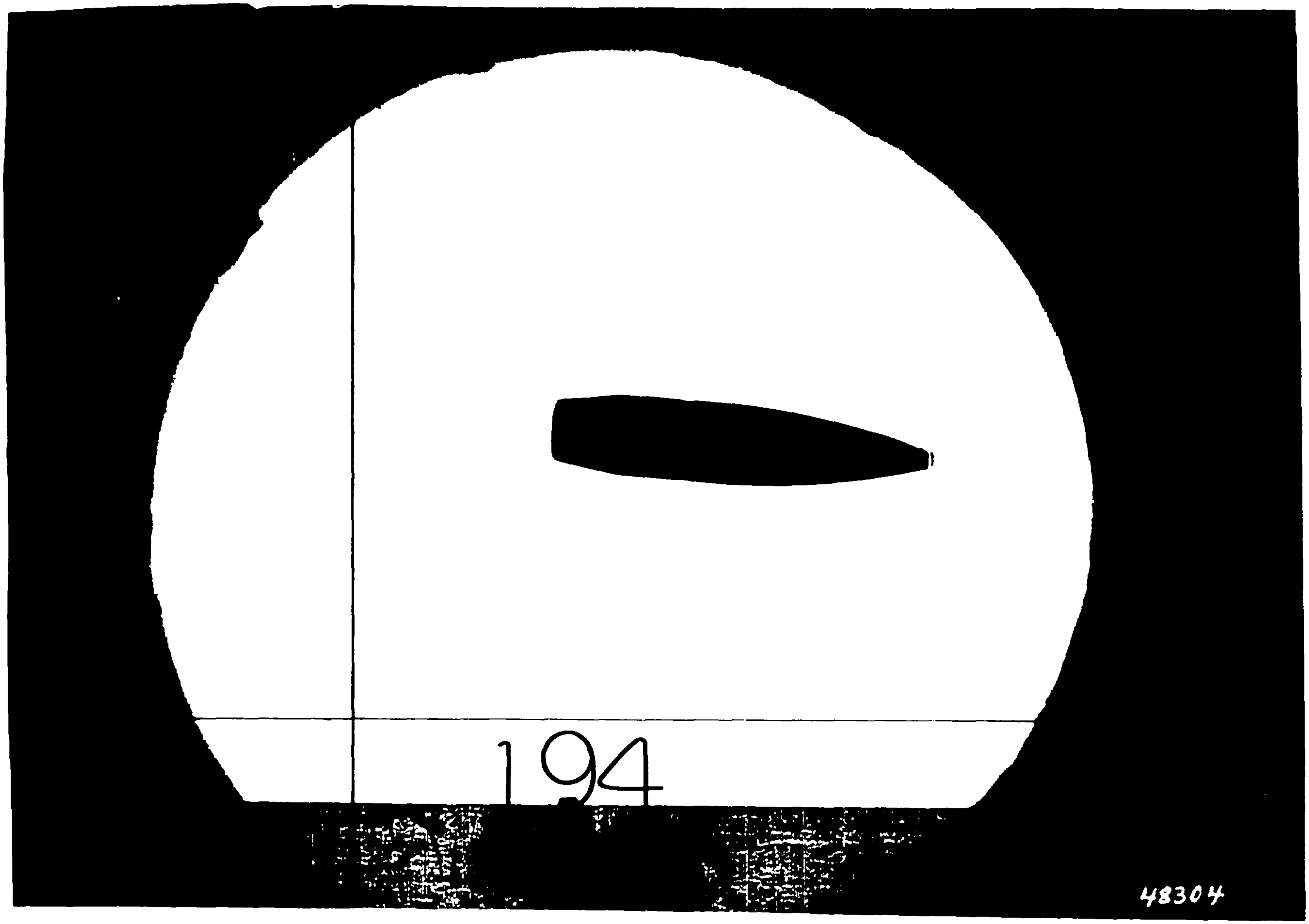
$\zeta = 0°0'$ $\eta = 0°5'$ $\delta = 0°5'$ $\phi = 90°$

Figure 14



Projectile, Caliber .30 M1922 AP Service Velocity
Projection on Horizontal Film

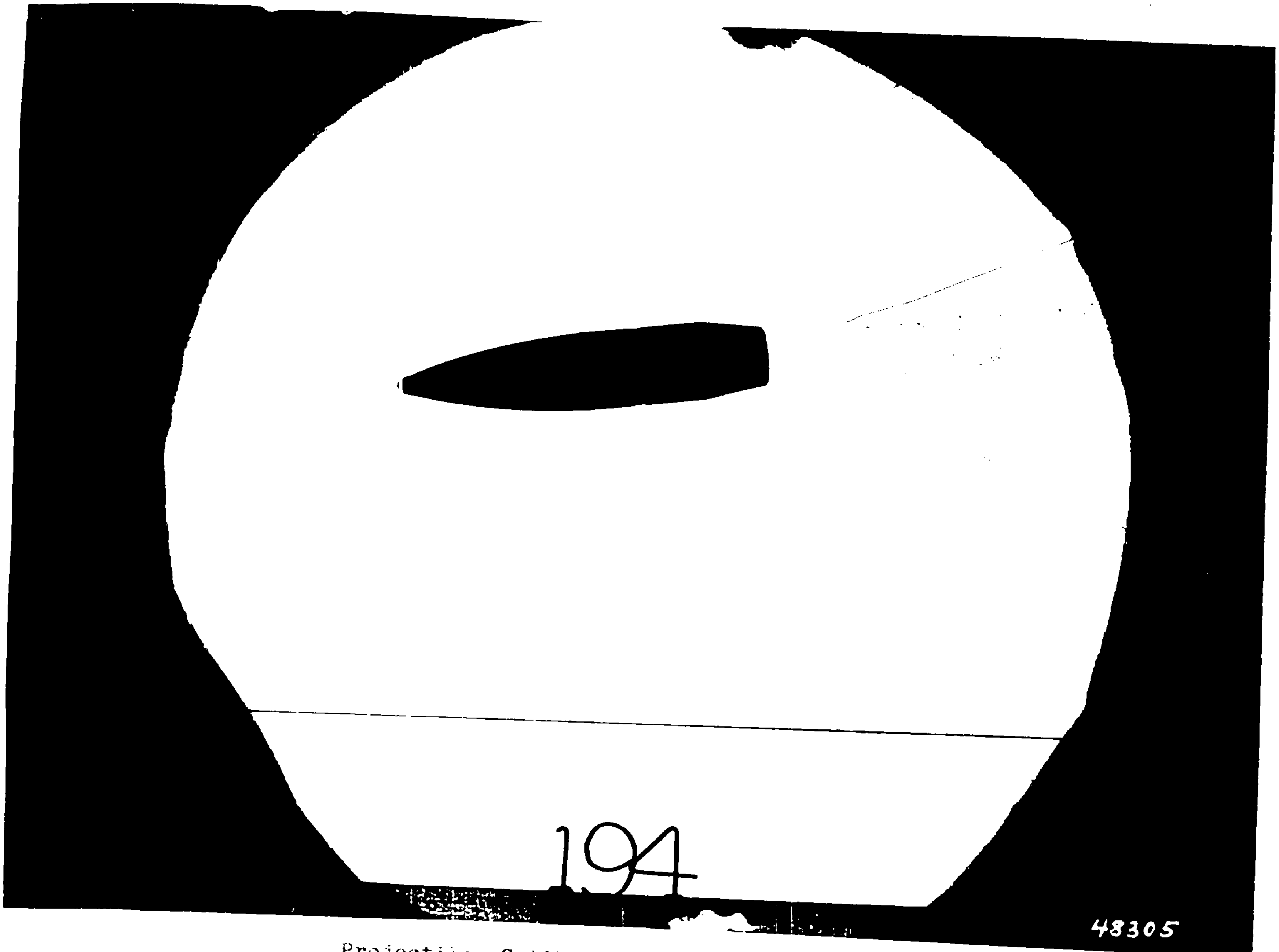
$\zeta = 0°0'$ $\eta = 0°5'$ $\delta = 0°5'$ $\varphi = 90°$



Projectile, Caliber .50 M1 AP Service Velocity
Projection on Vertical Film

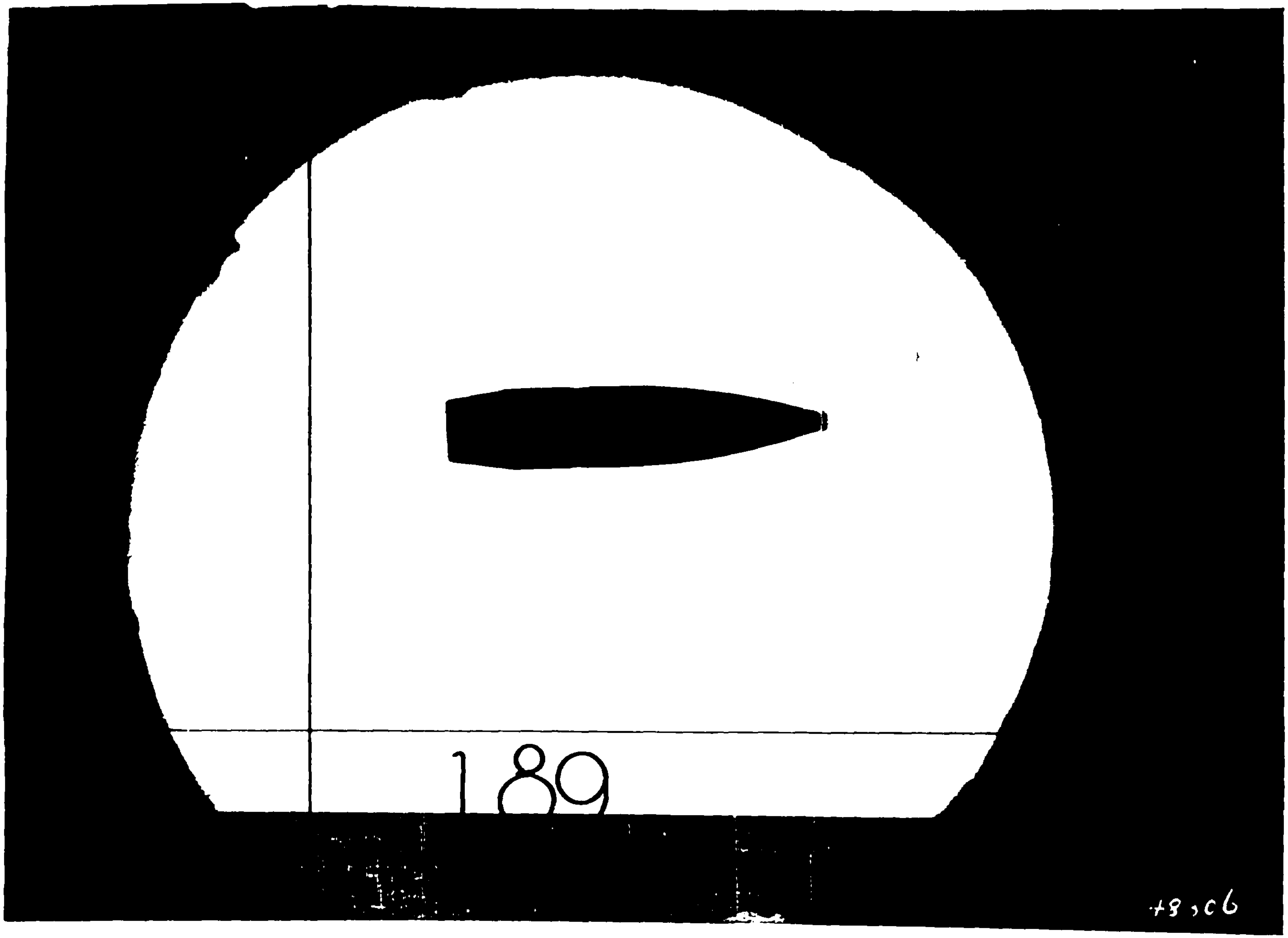
$\zeta = 6°42'$ $\eta = 4°52'$ $\delta = 8°15'$ $\varphi = 23°05'$

Figure 16



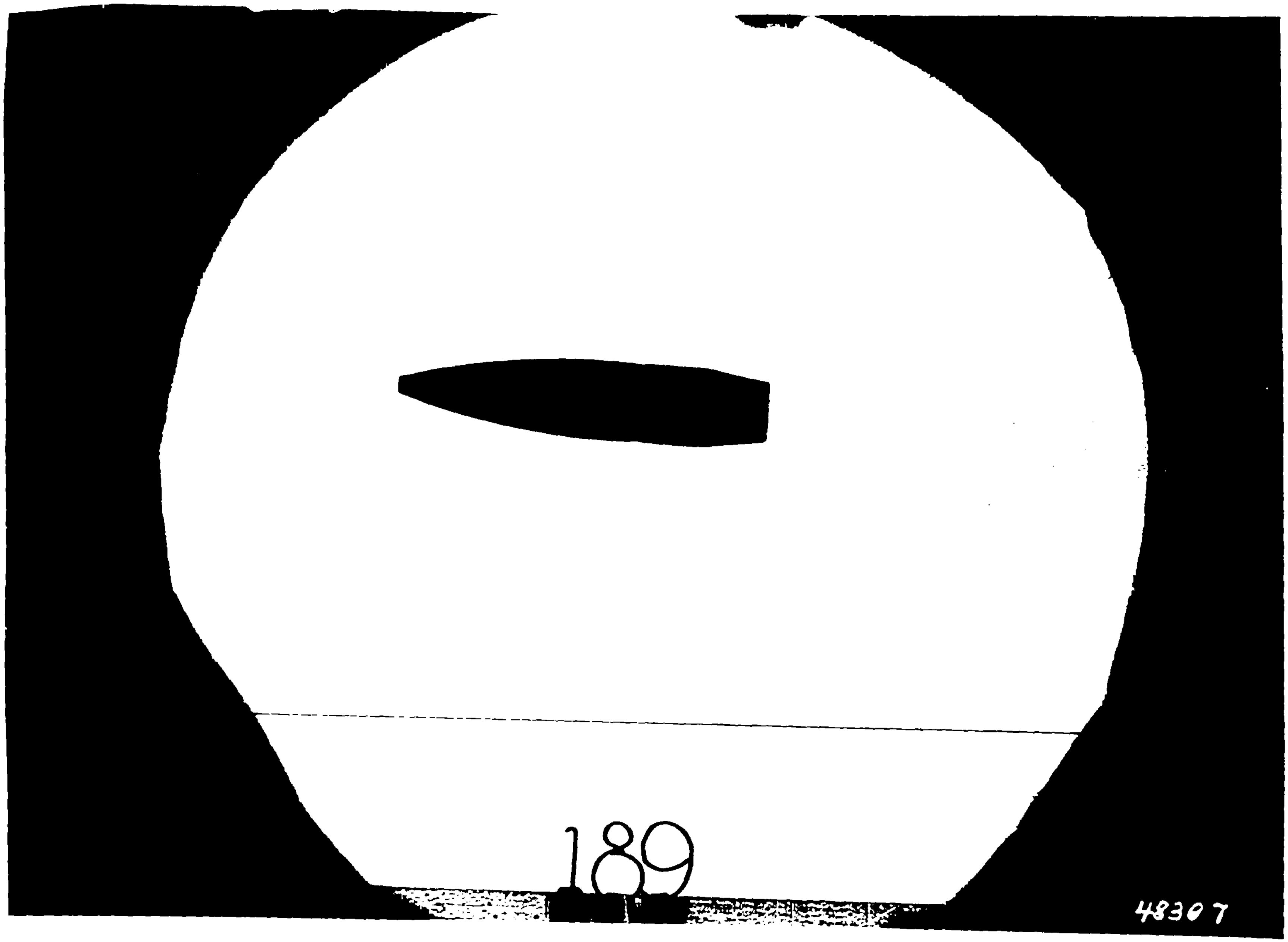
Projectile, Caliber .50 M1 AP Service Velocity
Projection on Horizontal Film

$\zeta = 6°4$[illegible]$'$ $\eta = 4°52'$ $\delta = 8°15'$ $\varphi = 234°05'$



Projectile, Caliber .50 M1 AP Service Velocity
Projection on Horizontal Film
$\zeta = 3°7'$ $\eta = 1°57'$ $\delta = 3°40'$ $\varphi = 58°0'$

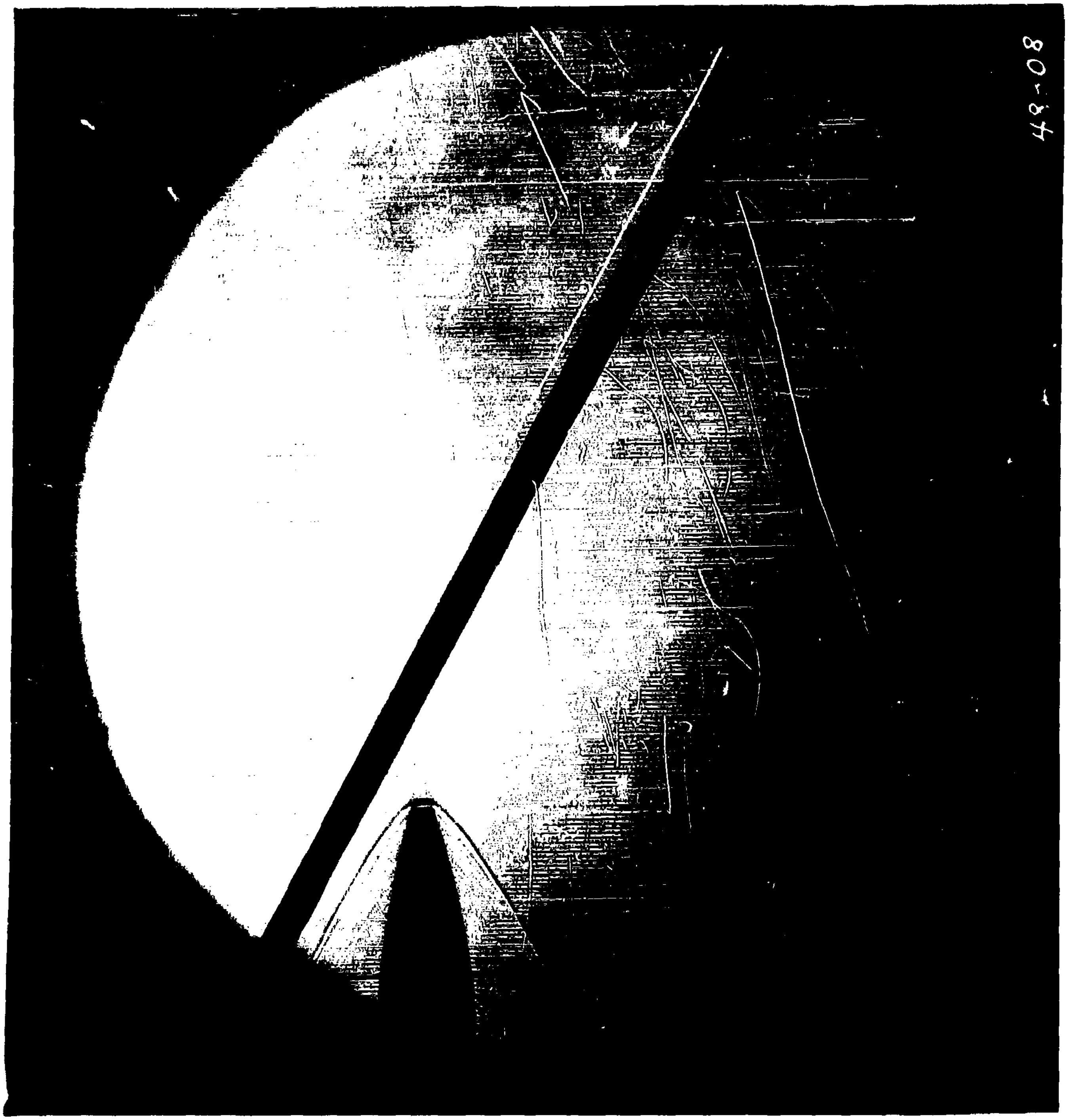
Figure 18



Projectile, Caliber .50 M1 AP Service Velocity
Projection on Vertical Film

$\zeta = 3°7'$ $\eta = 1°57'$ $\delta = 3°40'$ $\varphi = 58°0'$

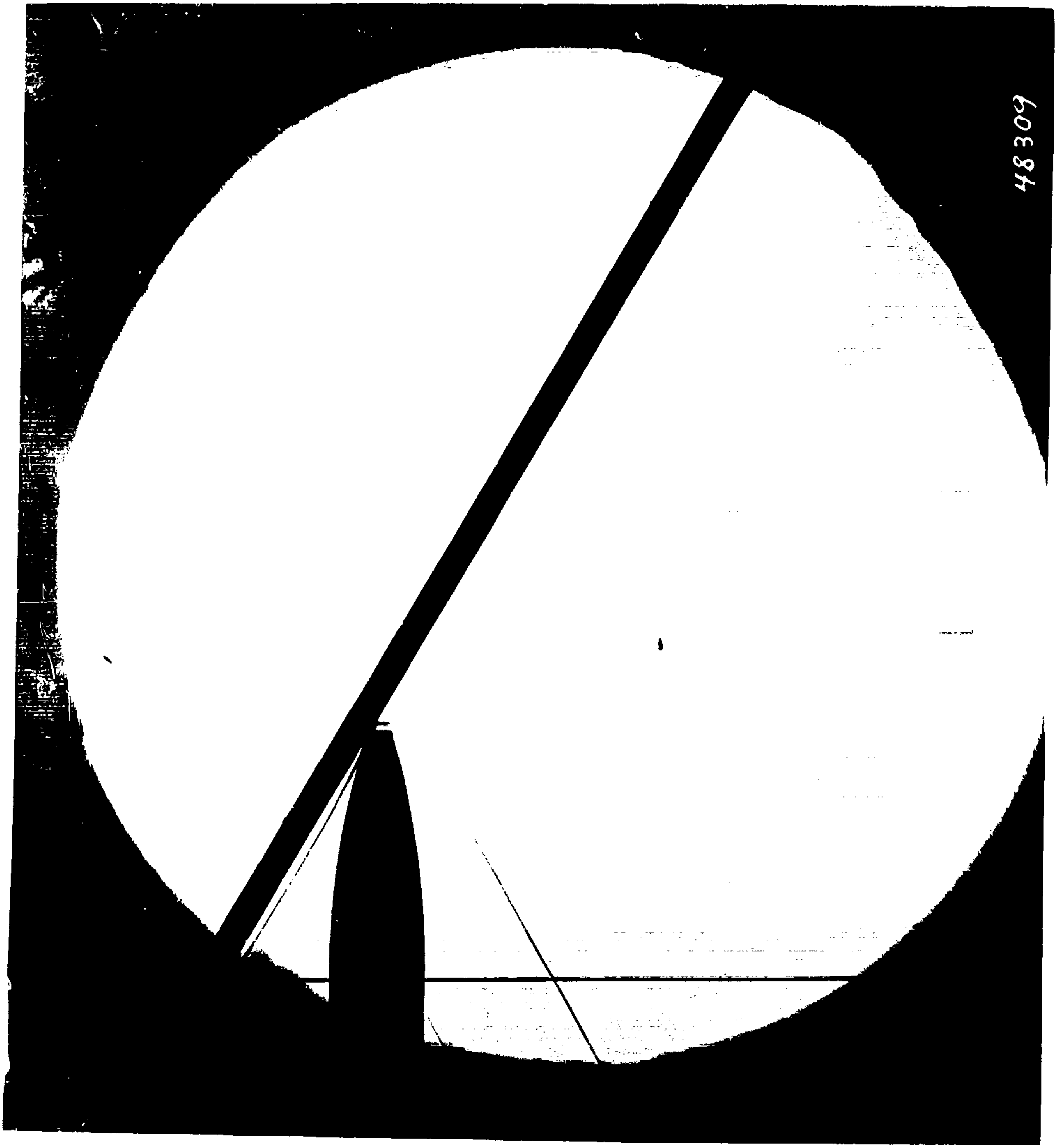
Figure 19



Projectile Penetrating 1/8 inch Dural at Angle of Impact 60°.

Caliber .50 M1 AP Service Velocity.

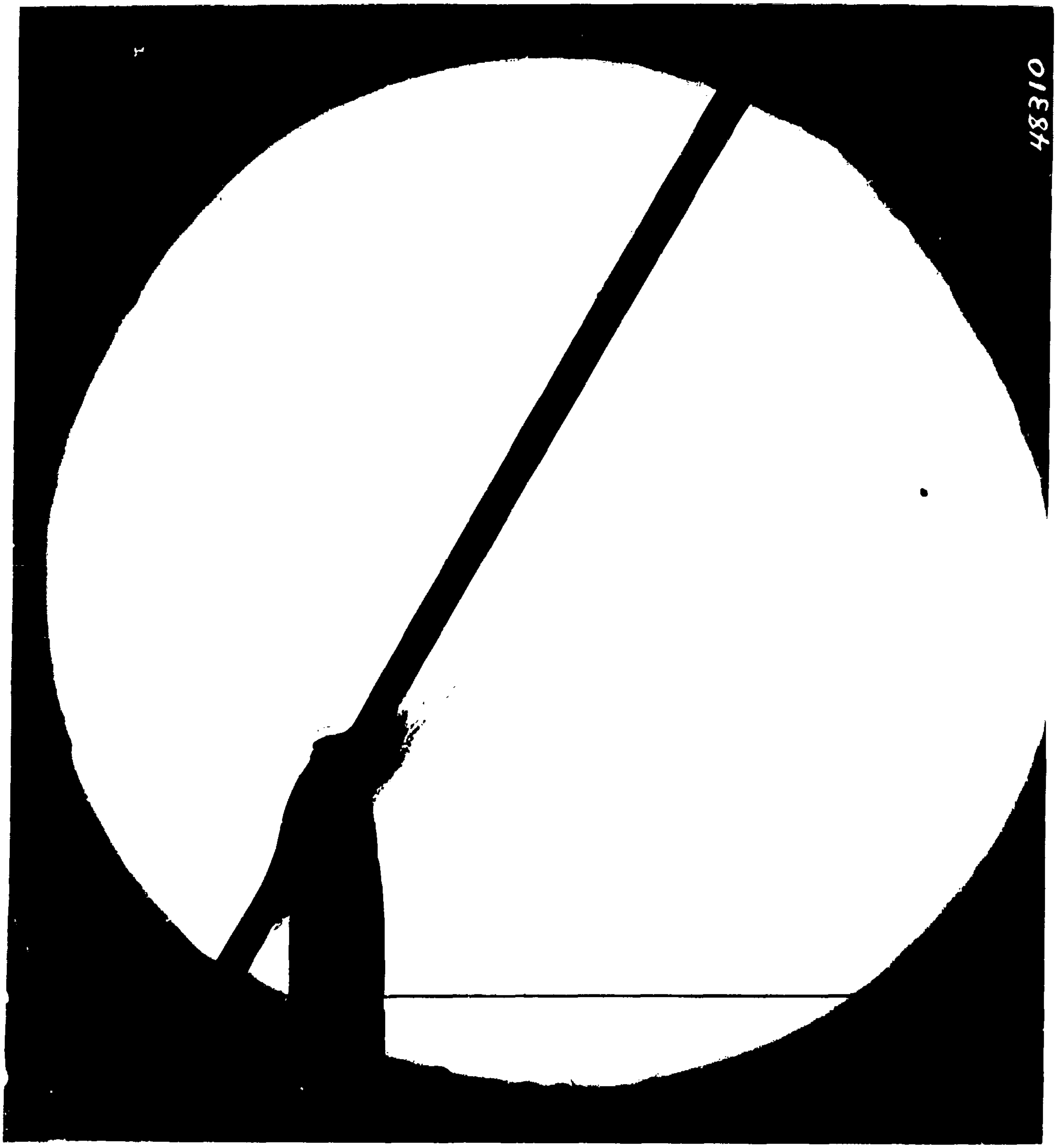
Figure 20



Projectile Penetrating 1/8 inch Dural at Angle of Impact 60°.

Caliber .50 M1 AP Service Velocity.

Figure 21



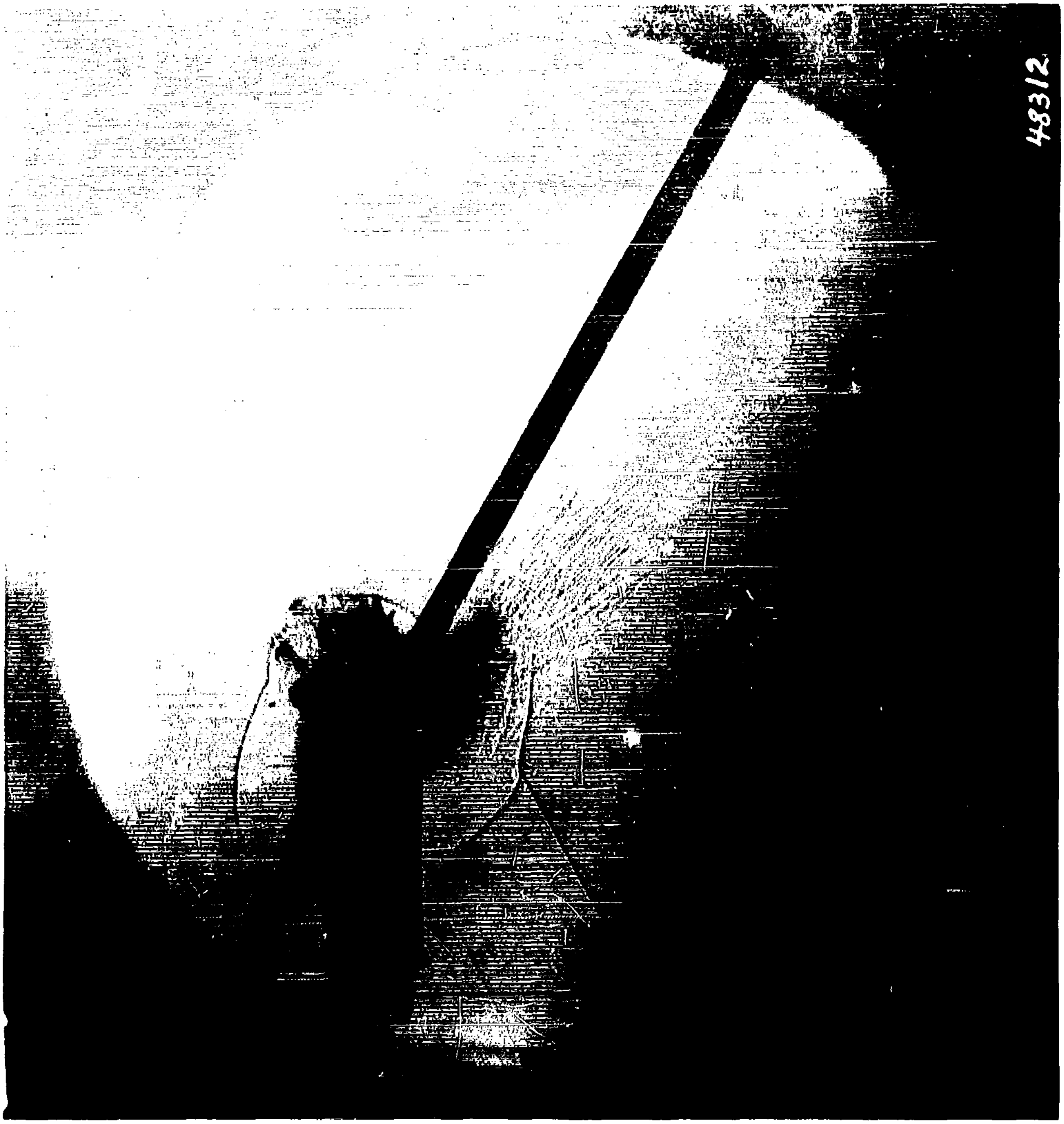
Projectile Penetrating 1/8 inch Dural at Angle of Impact 60°.

Caliber .50 M1 AP Service Velocity.

Projectile Penetrating 1/8 inch Dural at Angle of Impact 60°.

Caliber .50 M1 AP Service Velocity.

Figure 23



Projectile Penetrating 1/8 inch Dural at Angle of Impact 60°.

Caliber .50 M1 AP Service Velocity.

Projectile Penetrating 1/8 inch Dural at Angle of Impact 60°.

Caliber .50 M1 AP Service Velocity.

Projectile Penetrating 1/8 inch Dural at Angle of Impact 60°.

Caliber .50 M1 AP Service Velocity.

Figure 26

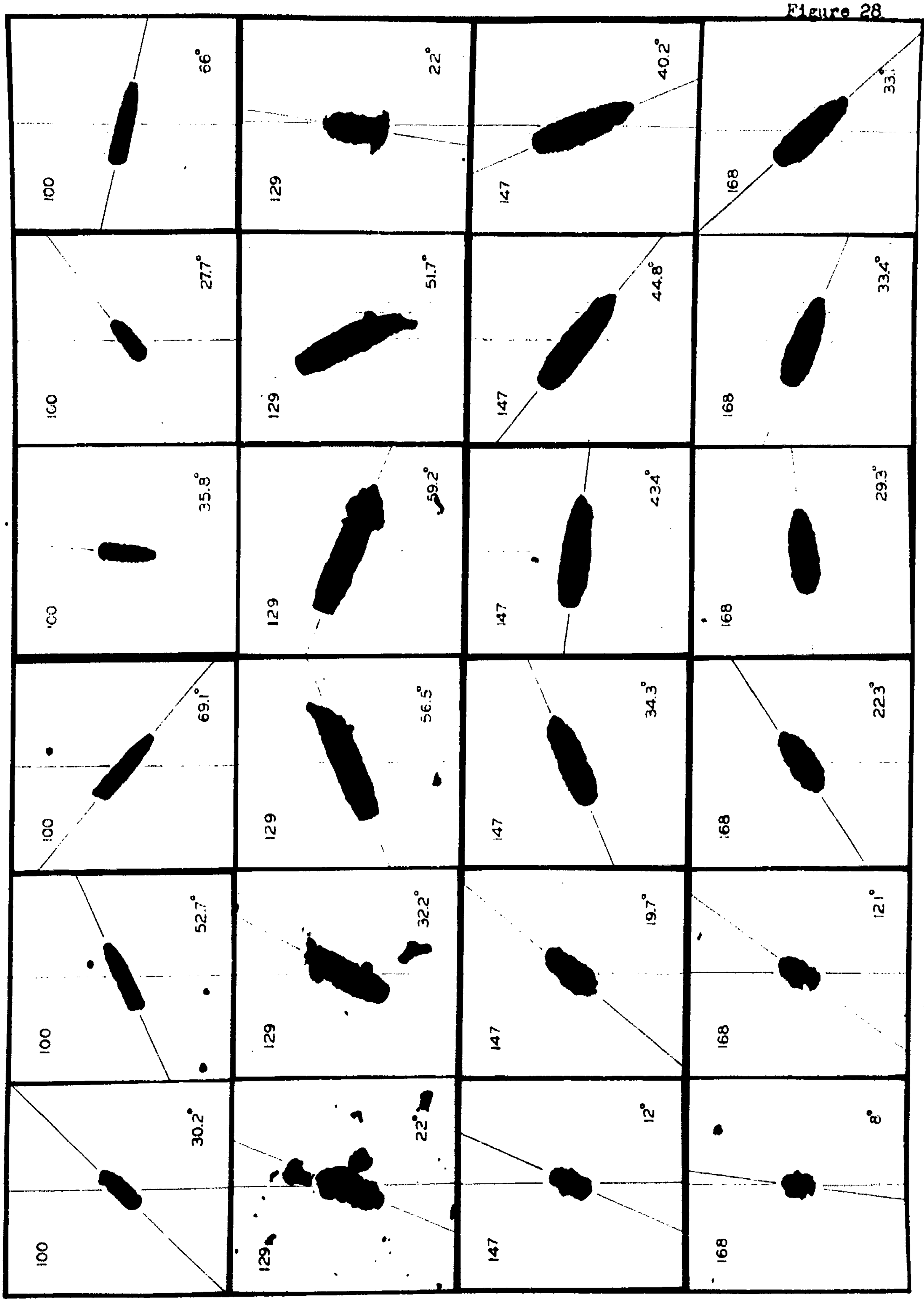
Projectile Penetrating 1/8 inch Dural at Angle of Impact 60°.

Caliber .50 M1 AP Service Velocity.

Projectile Penetrating 1/8 Dural at Angle of Impact 60°.

Caliber .50 M1 AP Service Velocity.

Figure 28



100
66°
129
22°
147
40.2°
168
33.1°
100
27.7°
129
51.7°
147
44.8°
168
33.4°
100
35.8°
129
59.2°
147
43.4°
168
29.3°
100
69.1°
129
56.5°
147
34.3°
168
22.3°
100
52.7°
129
32.2°
147
19.7°
168
12.1°
100
30.2°
129
22°
147
12°
168
8°

Figure 29

SPLASH CARDS CALIBER .50 PROJECTILE

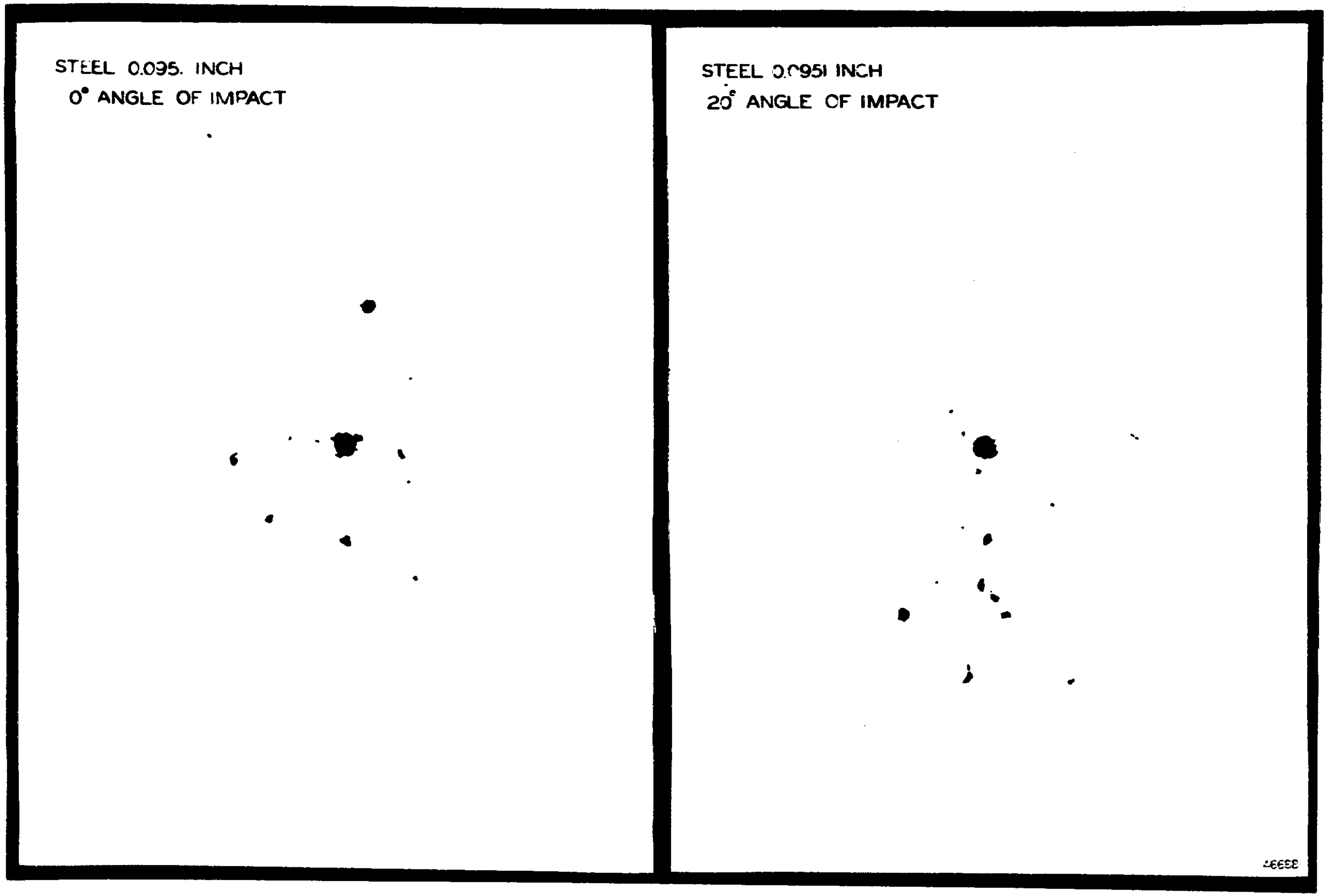


Figure 30

SPLASH CARDS CALIBER .50 PROJECTILE

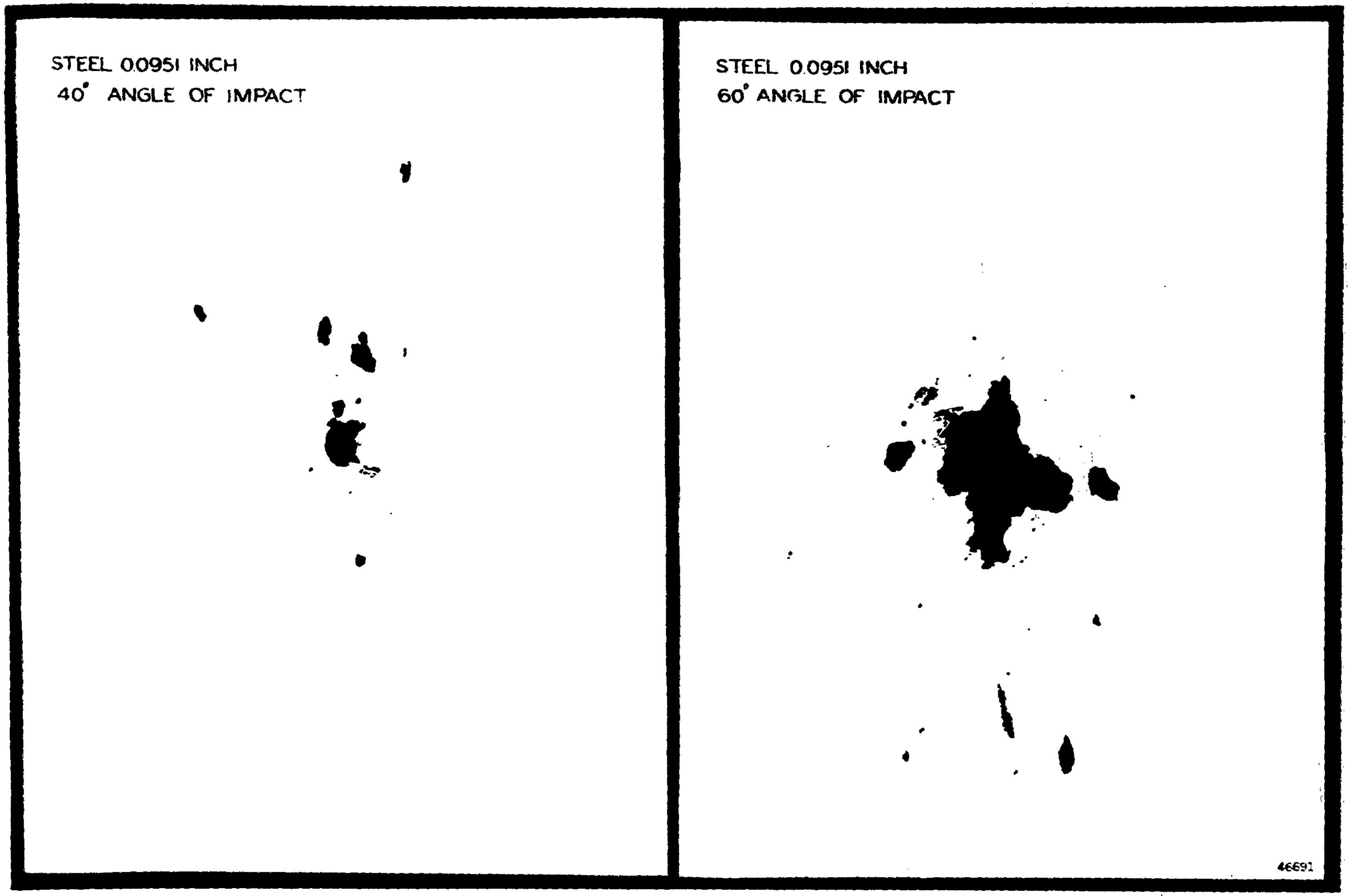


Figure 31

SPLASH CARDS CALIBER .50 PROJECTILE

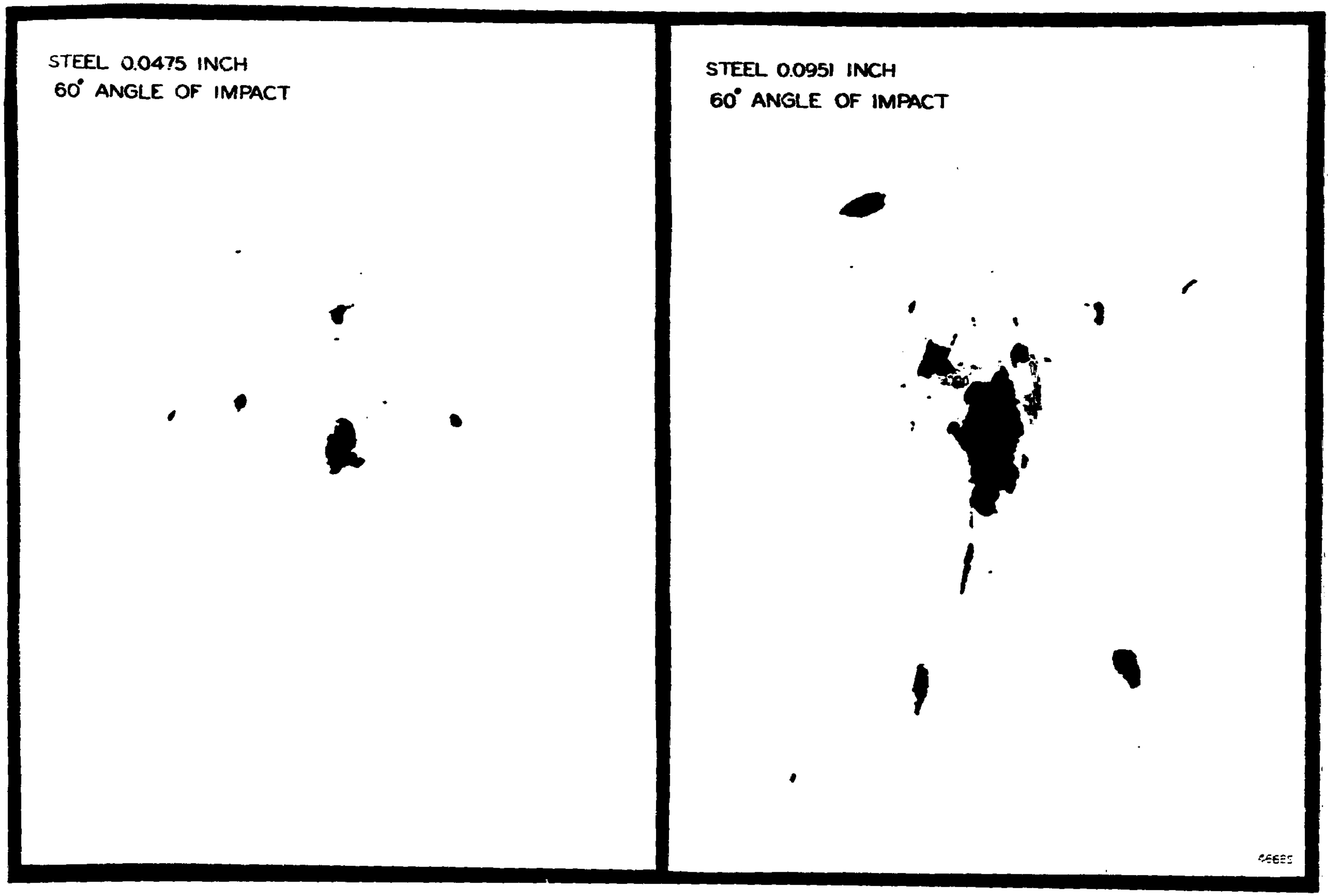
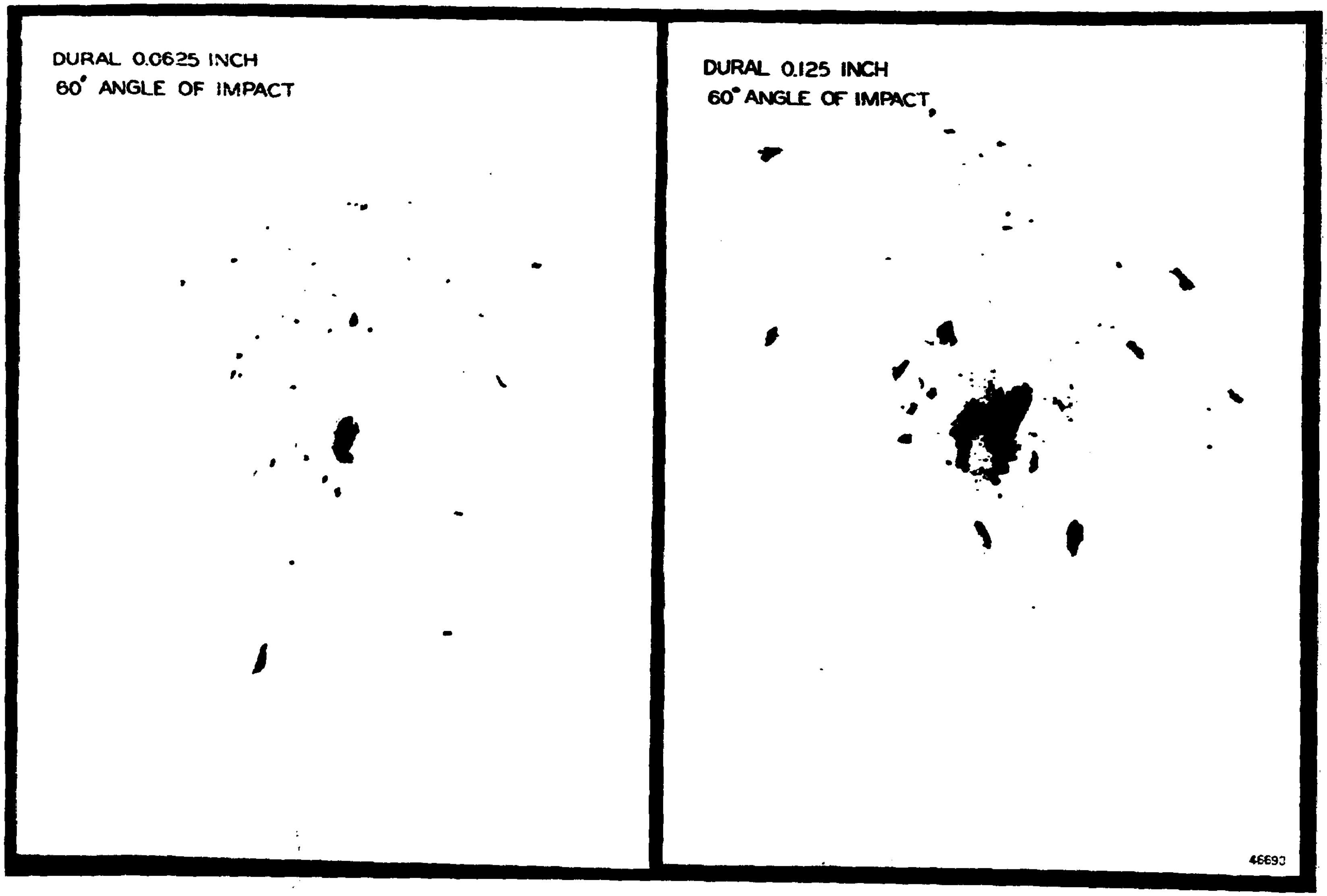


Figure 32

SPLASH CARDS CALIBER .50 PROJECTILE



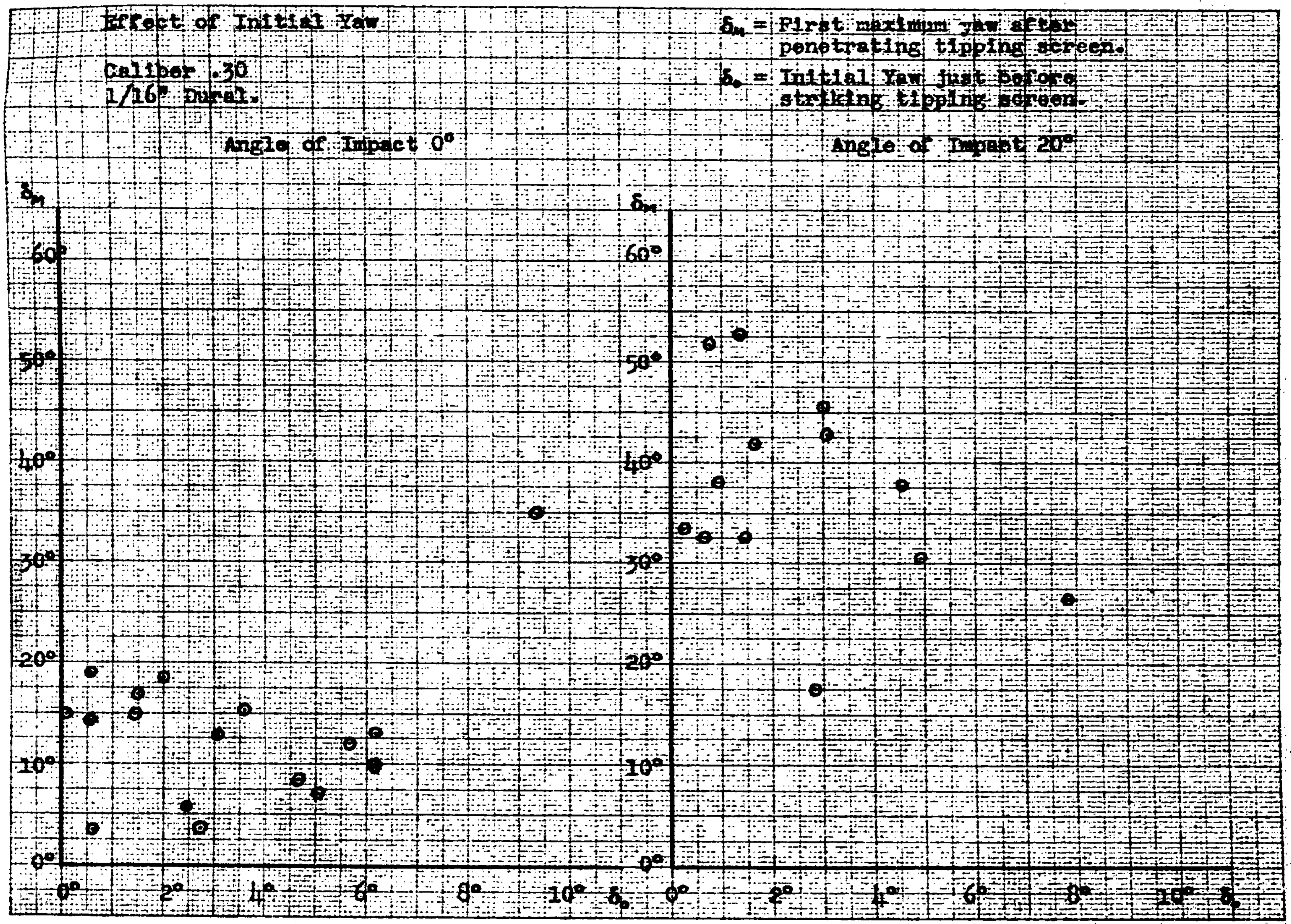
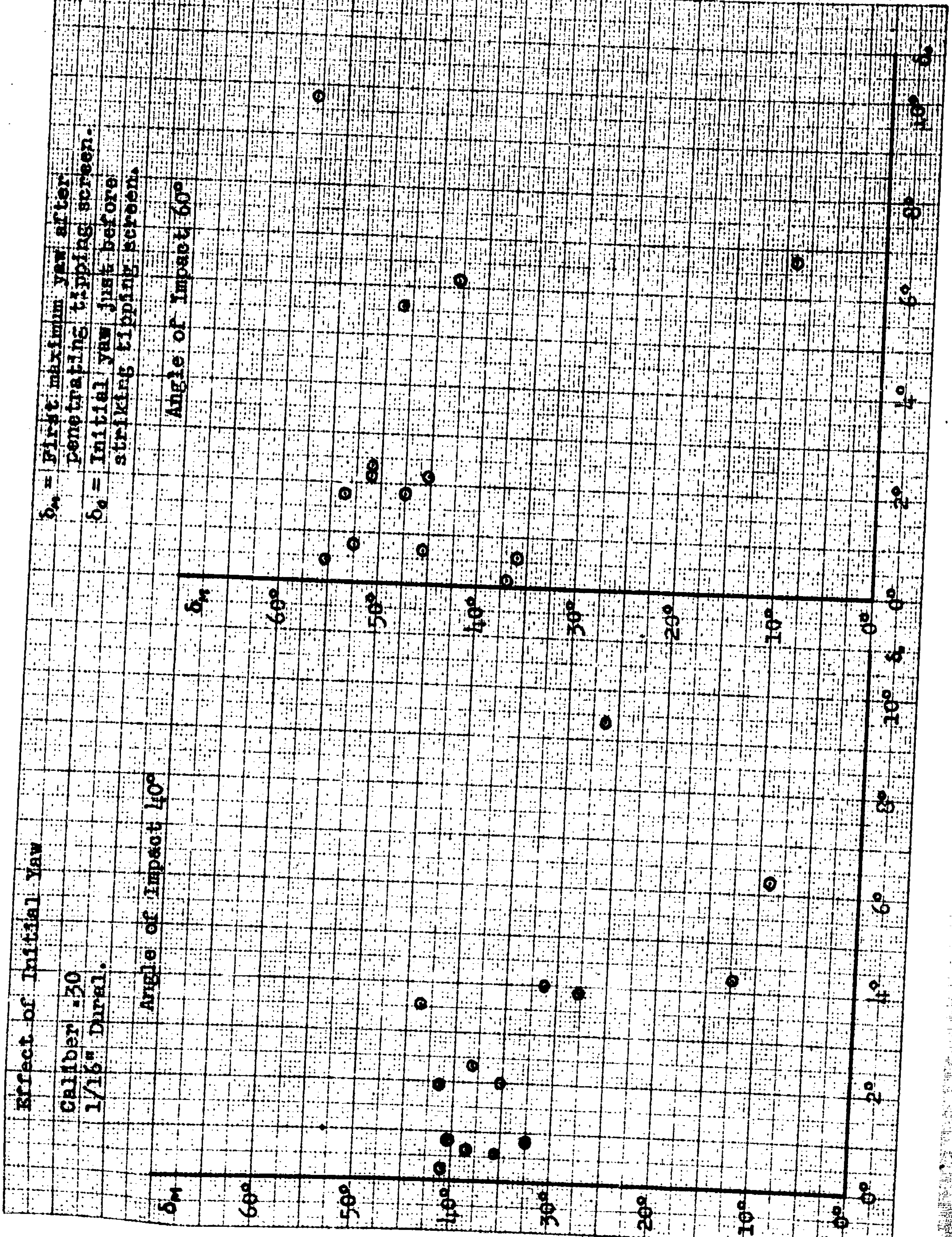

Effect of Initial Yaw
Caliber .30
1/16" Dural.
δ_M = First maximum yaw after penetrating tipping screen.
δ_o = Initial Yaw just before striking tipping screen.
Angle of Impact 0°
Angle of Impact 20°
δ_M
60°
50°
40°
30°
20°
10°
0°
2°
4°
6°
8°
10°
δ_o

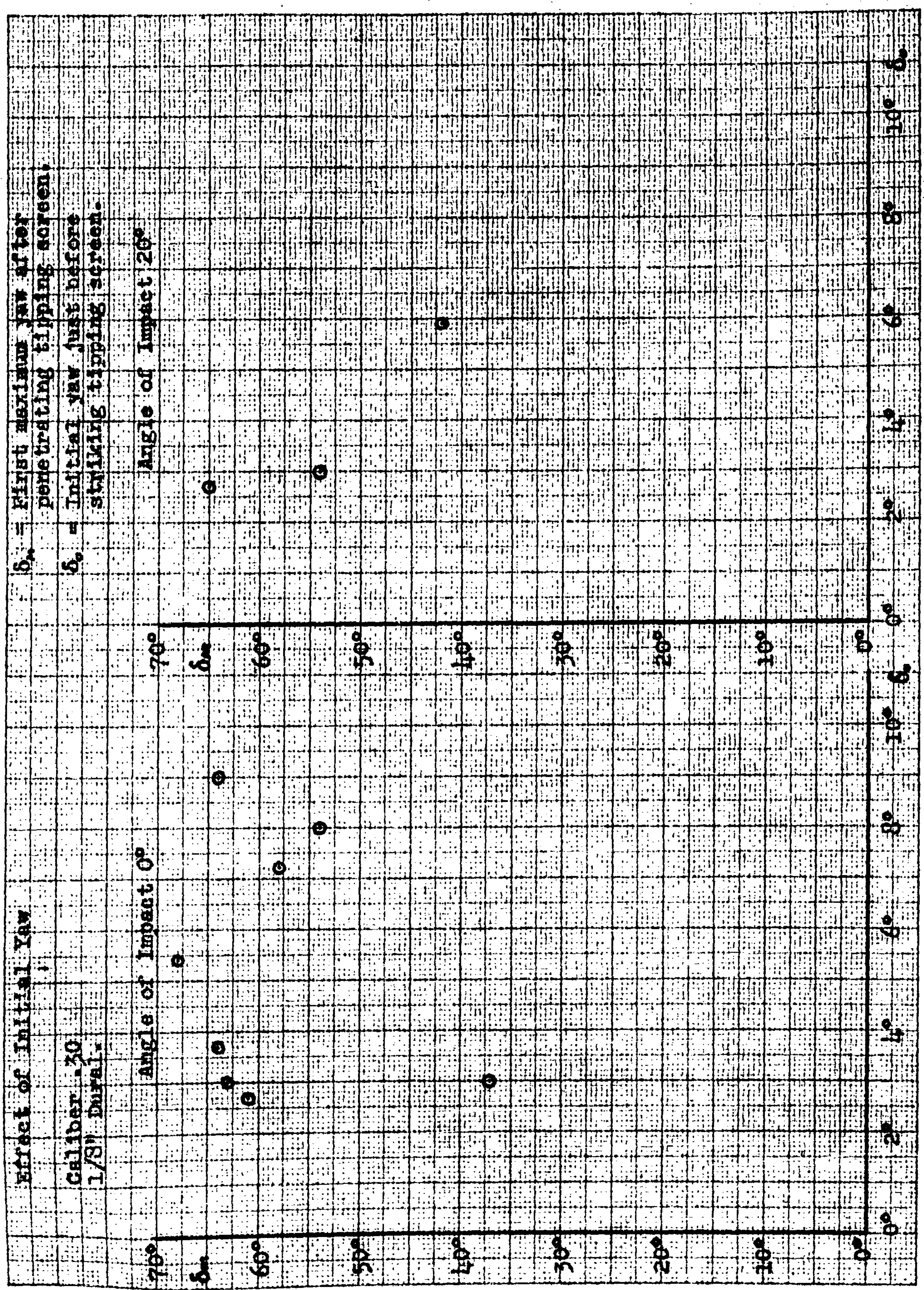
Figure 33

Figure 34



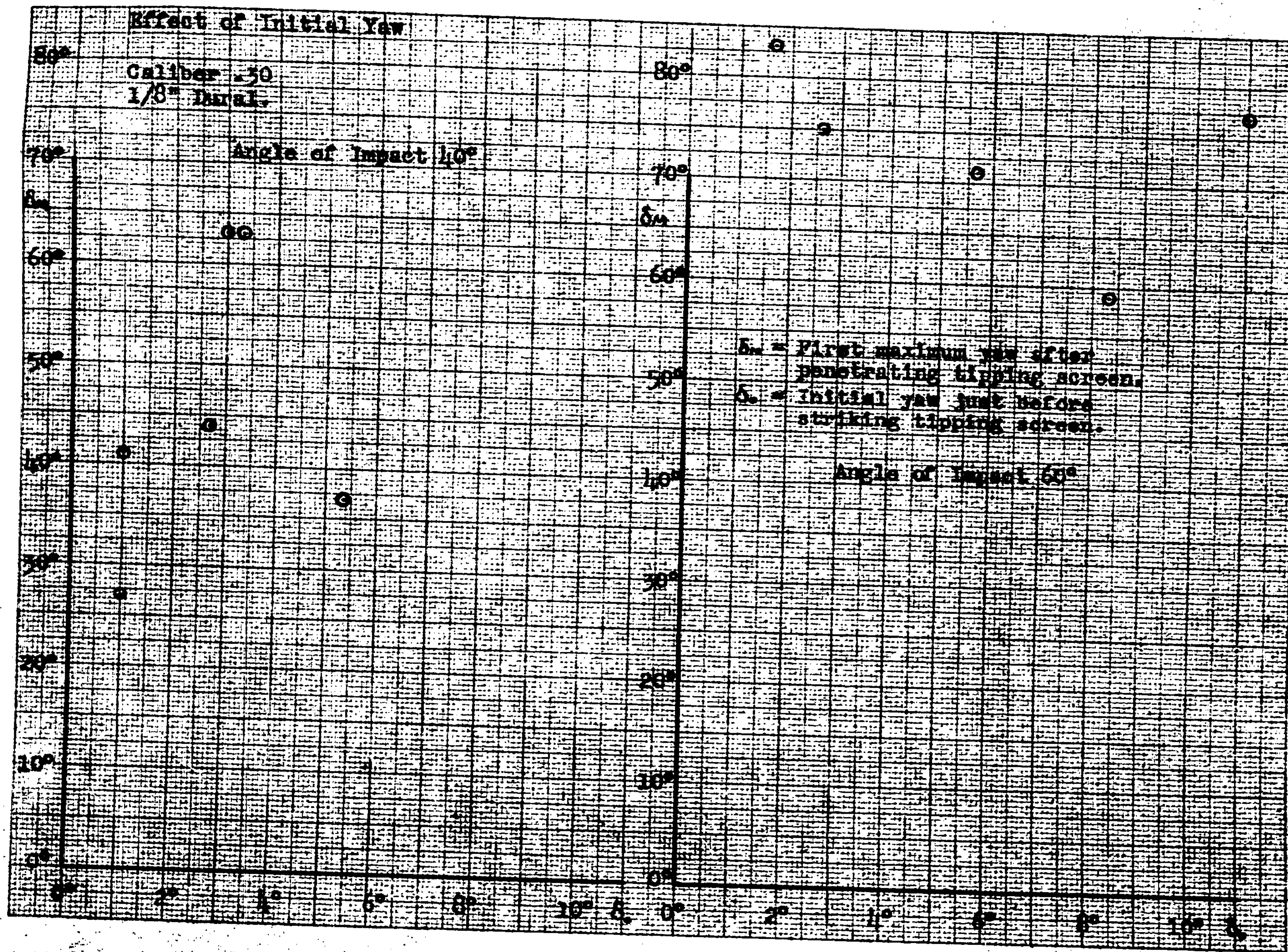
Effect of Initial Yaw
Caliber .30
1/16" Dural.
Angle of Impact 40°
δM = First maximum yaw after penetrating tipping screen.
δo = Initial yaw just before striking tipping screen.
Angle of Impact 60°
δM
60°
50°
40°
30°
20°
10°
0°
2°
4°
6°
8°
10°
δo

Figure 35



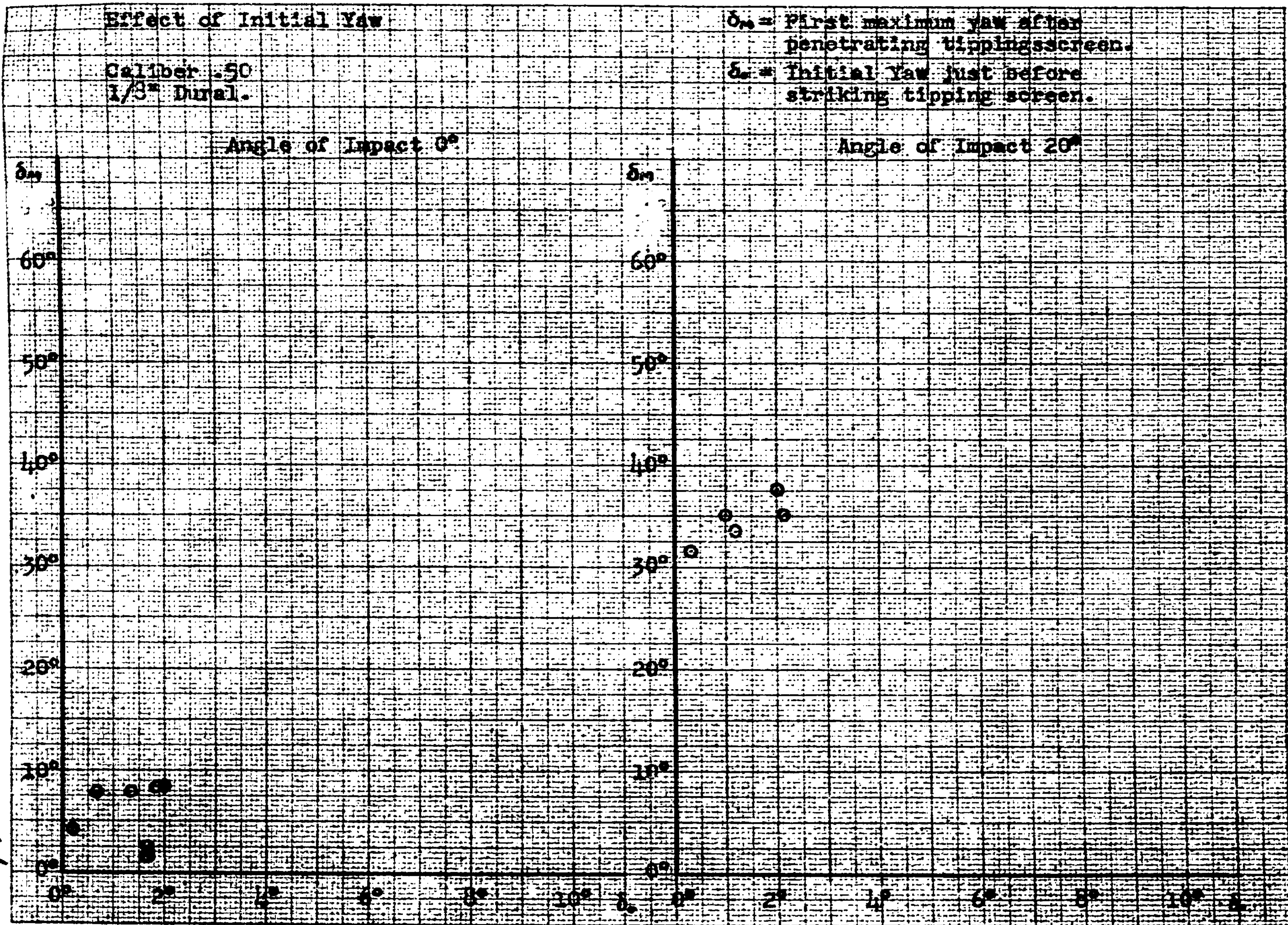
Effect of Initial Yaw
Caliber .30
1/8" Dural.
Angle of Impact 0°
δm = First maximum yaw after penetrating tipping screen.
δo = Initial yaw just before striking tipping screen.
Angle of Impact 20°
δm
δo

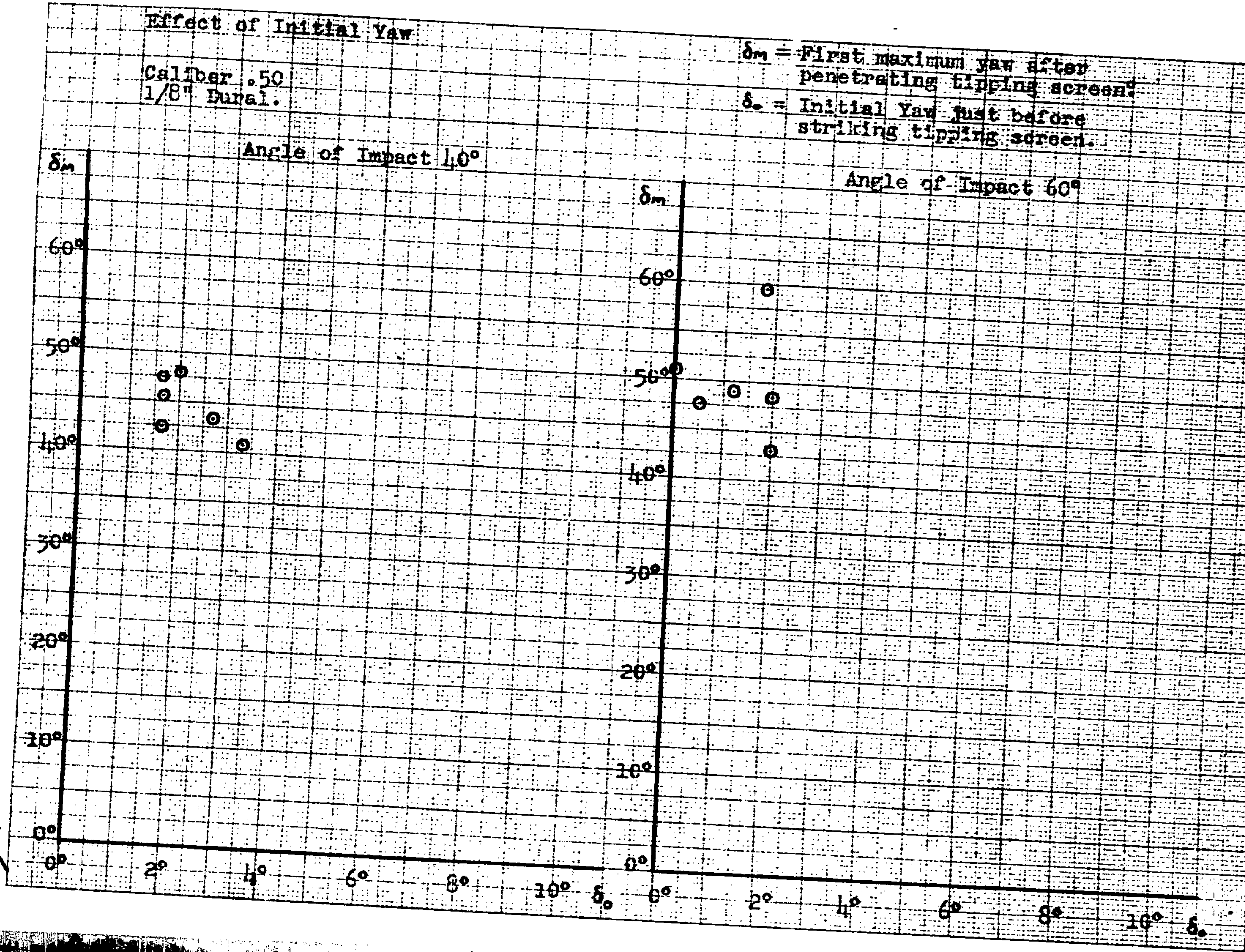
Figure 36



Effect of Initial Yaw
Caliber .30
1/8" Dural.
Angle of Impact 40°
Angle of Impact 60°
δ_M = First maximum yaw after penetrating tipping screen.
δ_0 = Initial yaw just before striking tipping screen.
δ_M
δ_0
0°
10°
20°
30°
40°
50°
60°
70°
80°
2°
4°
6°
8°
10°

Figure 37

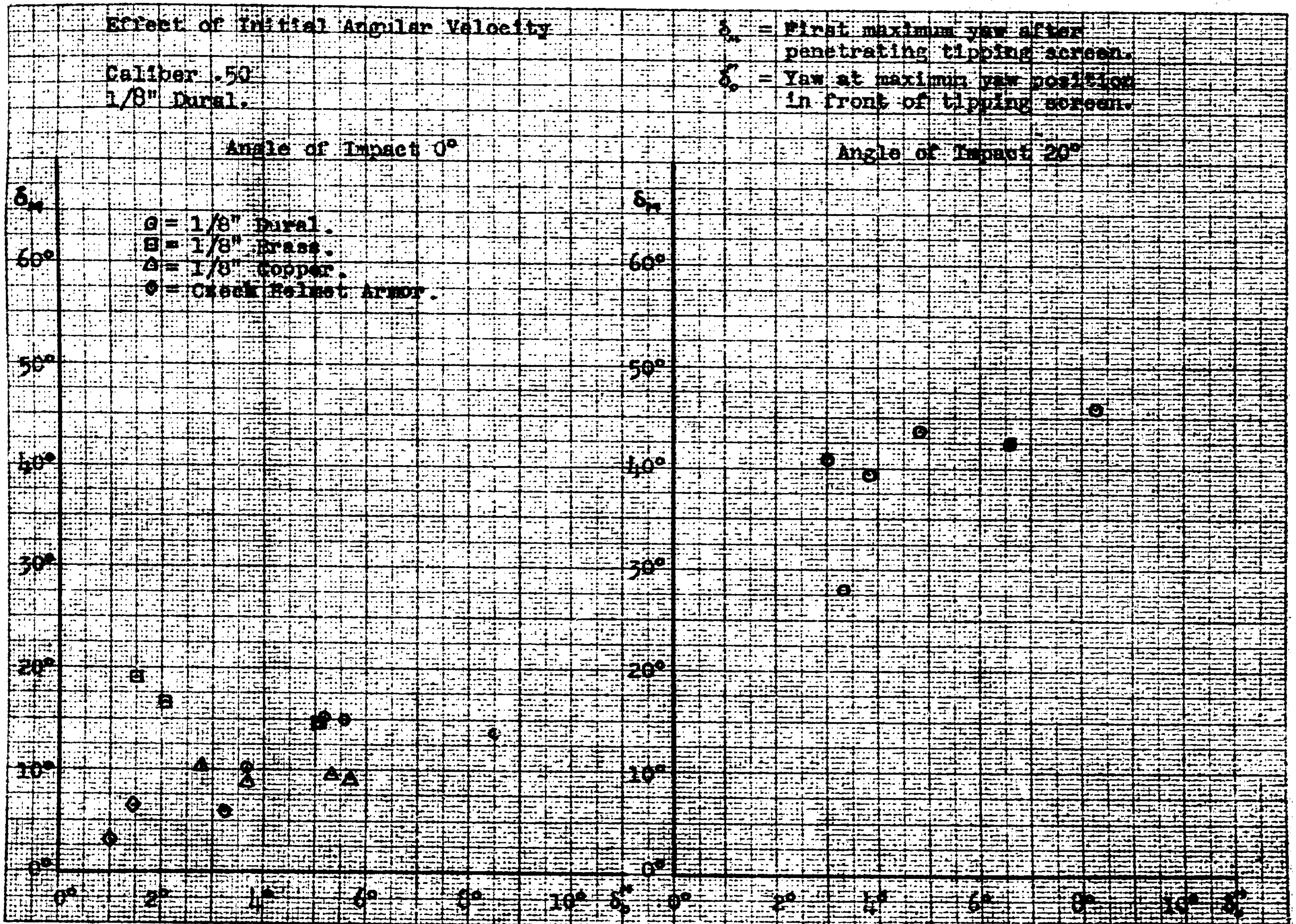

Effect of Initial Yaw
Caliber .50
1/8" Dural.
δ_m = First maximum yaw after penetrating tippingsscreen.
δ_o = Initial Yaw just before striking tipping screen.
Angle of Impact 0°
Angle of Impact 20°
δ_m
60°
50°
40°
30°
20°
10°
0°
2°
4°
6°
8°
10°
δ_o



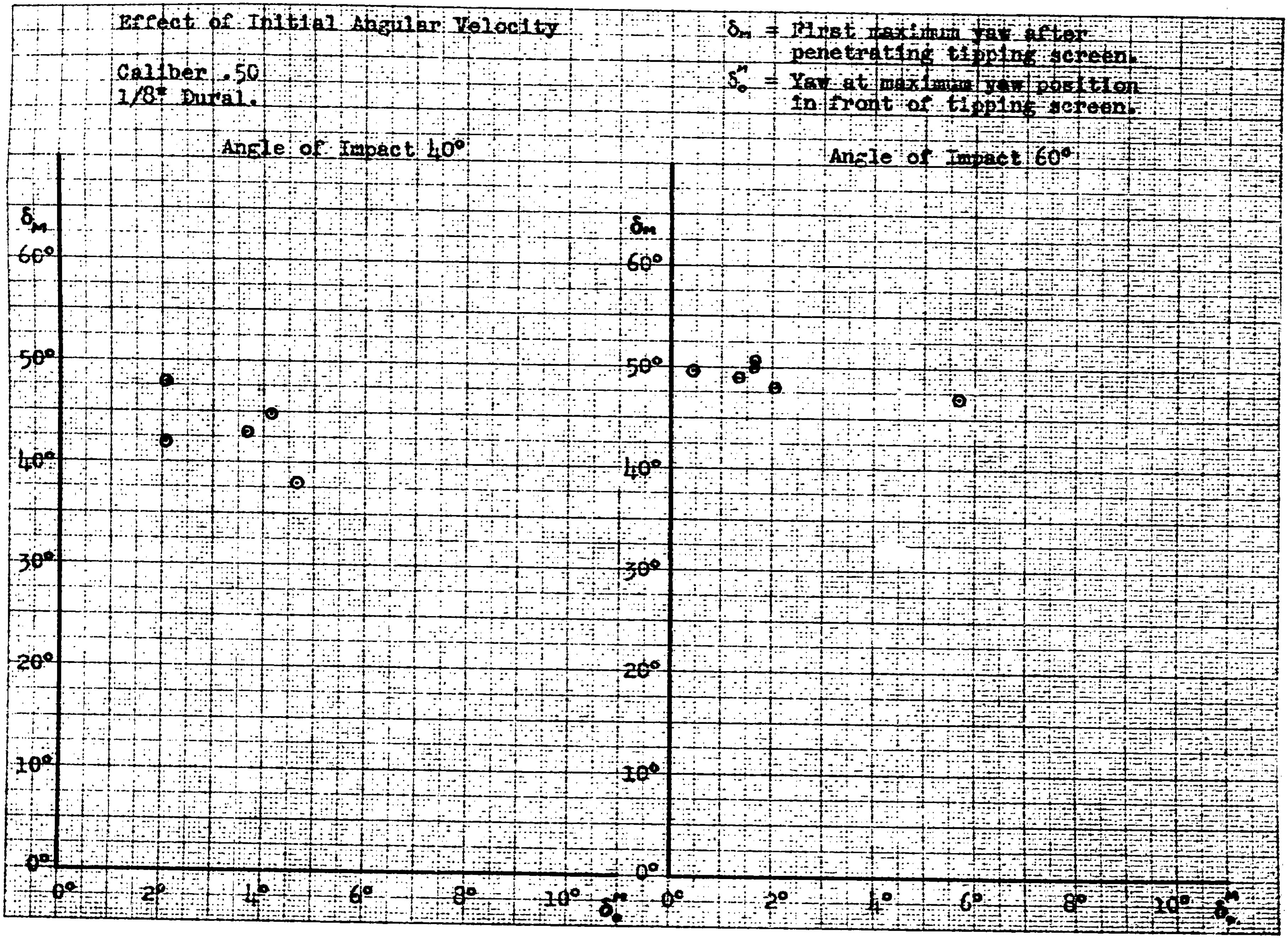
Effect of Initial Yaw
Caliber .50
1/8" Dural.
δ_m = First maximum yaw after penetrating tipping screen.
δ_o = Initial Yaw just before striking tipping screen.
Angle of Impact 40°
Angle of Impact 60°
δ_m
60°
50°
40°
30°
20°
10°
0°
2°
4°
6°
8°
10°
δ_o

Figure 38

Figure 39



Effect of Initial Angular Velocity
Caliber .50
1/8" Dural.
δ_m = First maximum yaw after penetrating tipping screen.
δ_o = Yaw at maximum yaw position in front of tipping screen.
Angle of Impact 0°
Angle of Impact 20°
⊙ = 1/8" Dural.
⊟ = 1/8" Brass.
△ = 1/8" Copper.
◈ = Czech Helmet Armor.
δ_m
60°
50°
40°
30°
20°
10°
0°
2°
4°
6°
8°
10°
δ_o



Effect of Initial Angular Velocity
Caliber .50
1/8" Dural.
δ_M = First maximum yaw after penetrating tipping screen.
δ_o^M = Yaw at maximum yaw position in front of tipping screen.
Angle of Impact 40°
Angle of Impact 60°
δ_M
60°
50°
40°
30°
20°
10°
0°
2°
4°
6°
8°
10°
δ_o^M

Figure 40

Figure 41

Hole Made in 1/16" Dural by Caliber .30 M1922 A.P. Projectile

Front　　　　Cross Section　　　　Rear

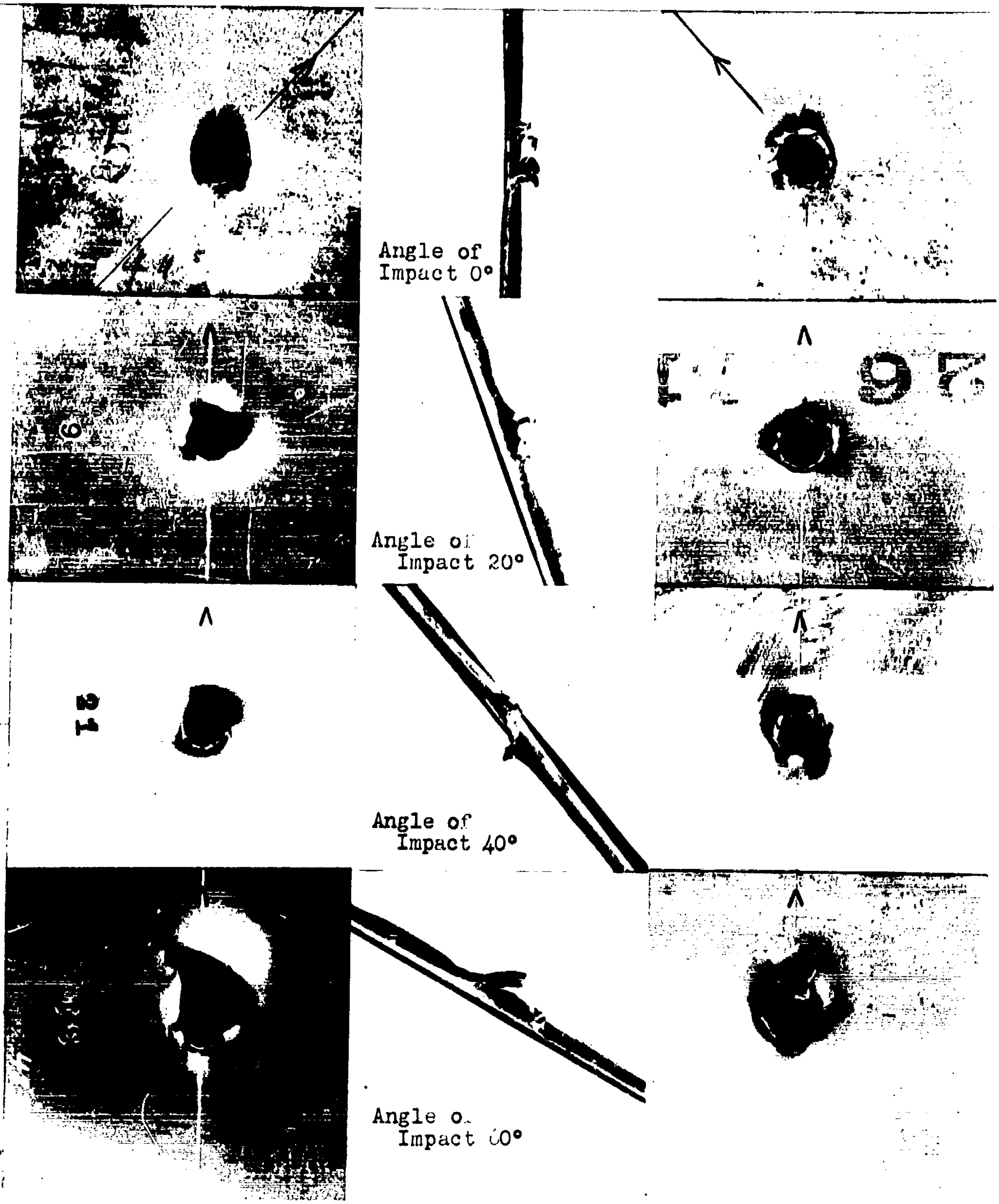
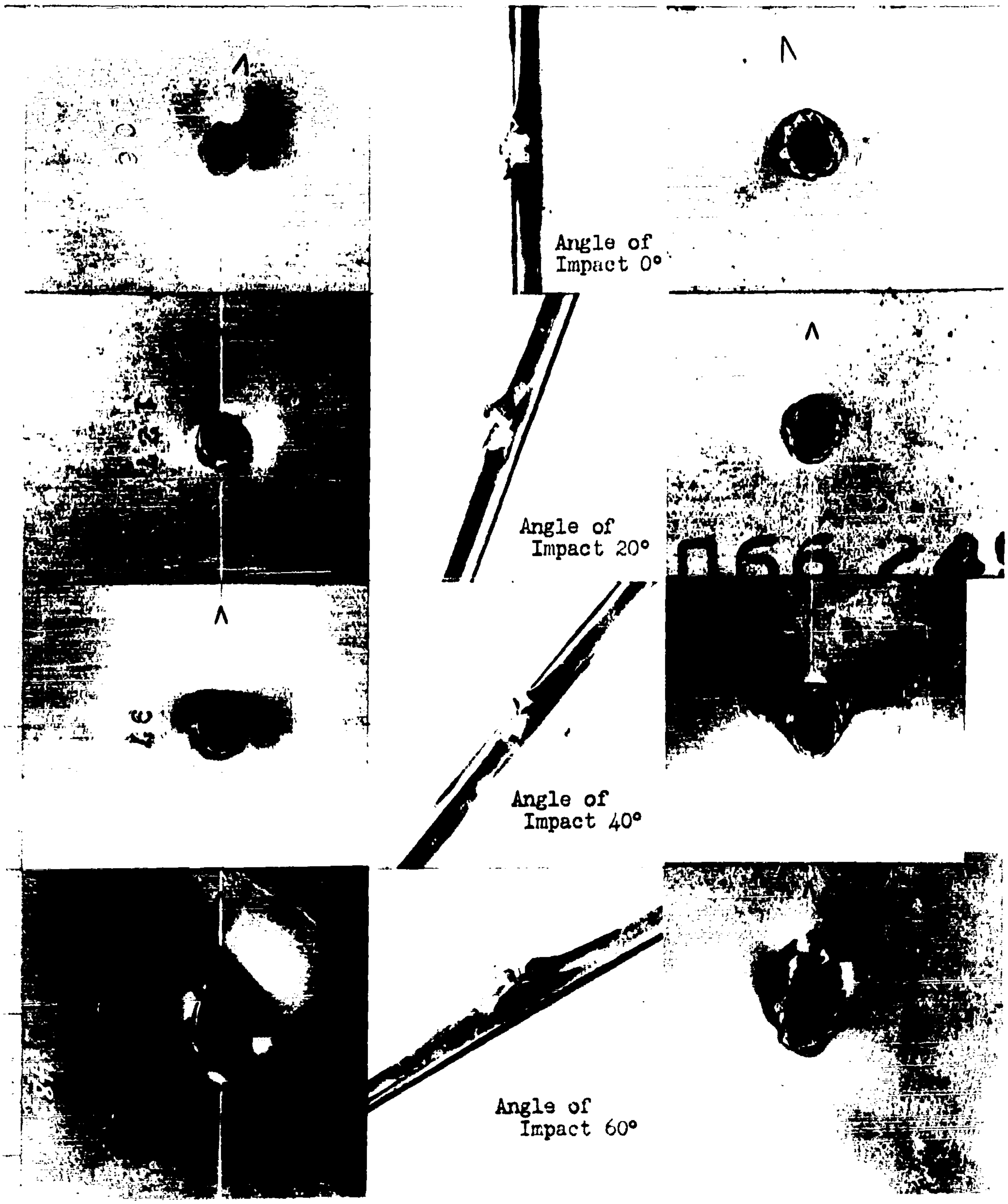


Figure 42

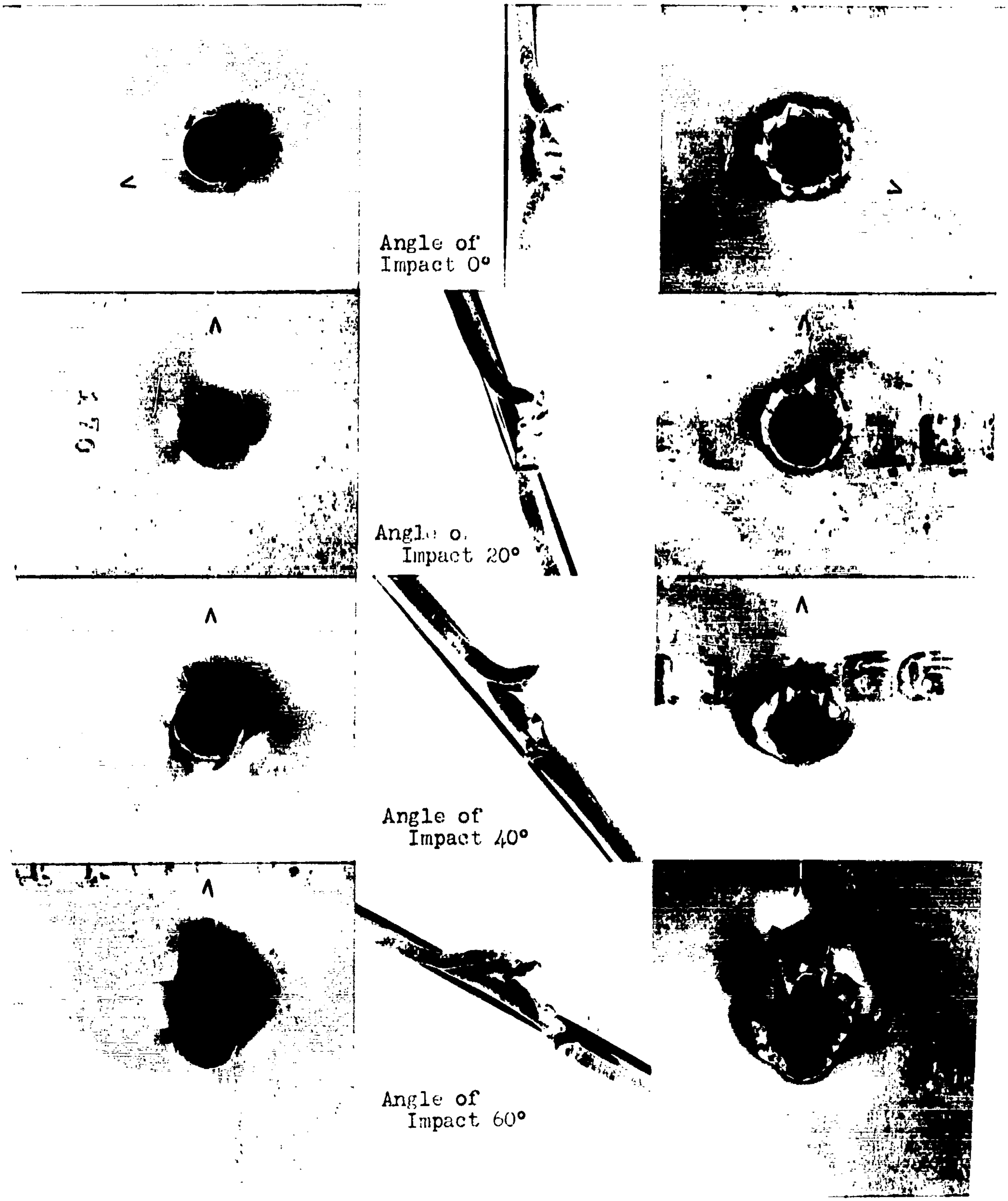
Hole Made in 1/8" Dural by Caliber .30 M1922 A.P. Projectile

Front | Cross Section | Rear



Hole Made in 1/8" Dural by Caliber .50 M1 A.P. Projectile

Front | Cross Section | Rear



Hole Made in 0.0475" Steel by Caliber .50 M1 A.P. Projectile

Front | Cross Section | Rear

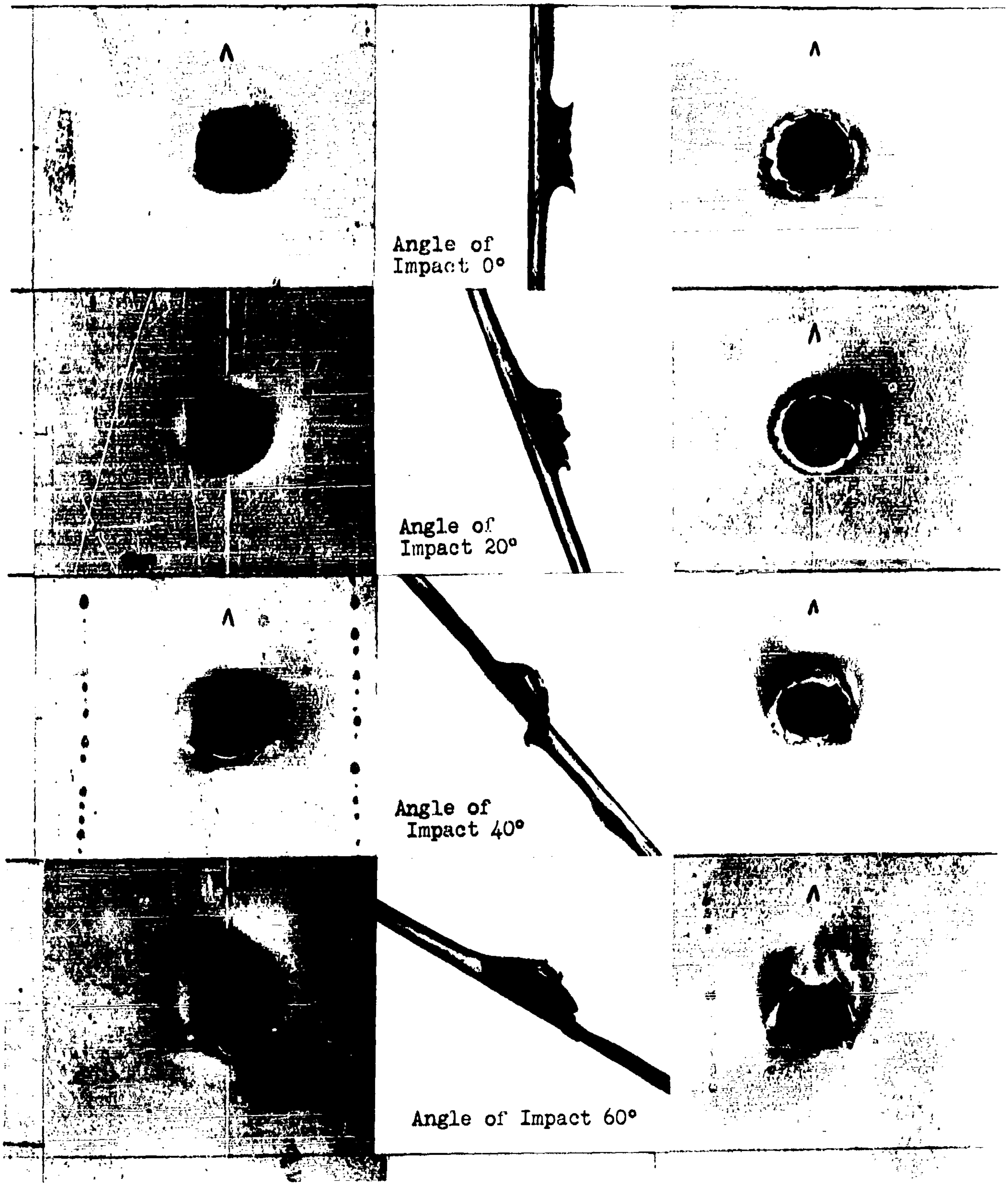
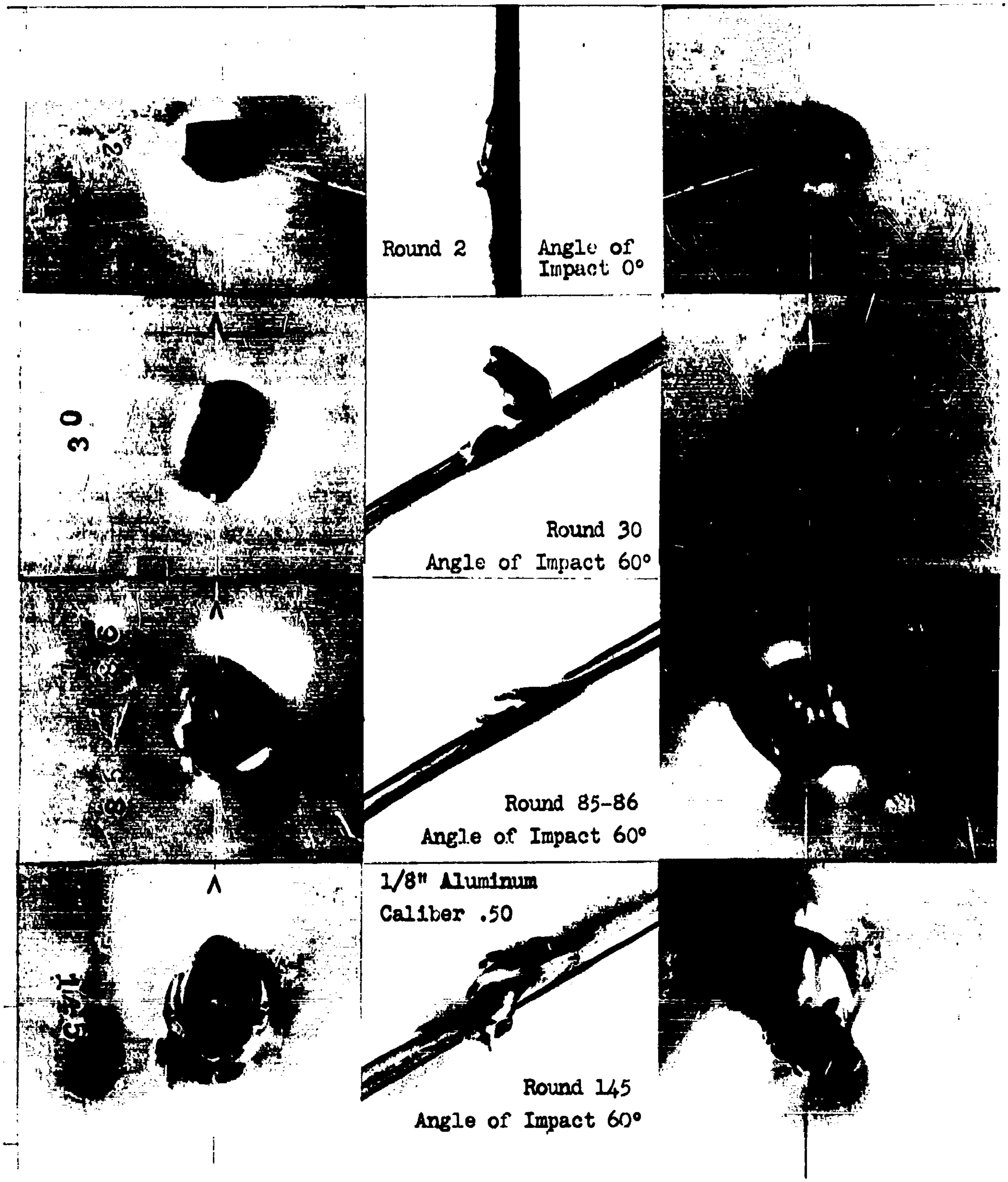


Figure 45

Hole Made in 1/16" Dural by Caliber .30 M1922 A.P. Projectile

Front Cross Section Rear



COURSE OF ORIENTATION THRU TIPPING SCREEN

1/16" Dural Screen — Maximum Yaw Position

Caliber .30 M1922 A.P. Projectile

O = Entrance Orientation — → = Exit Orientation

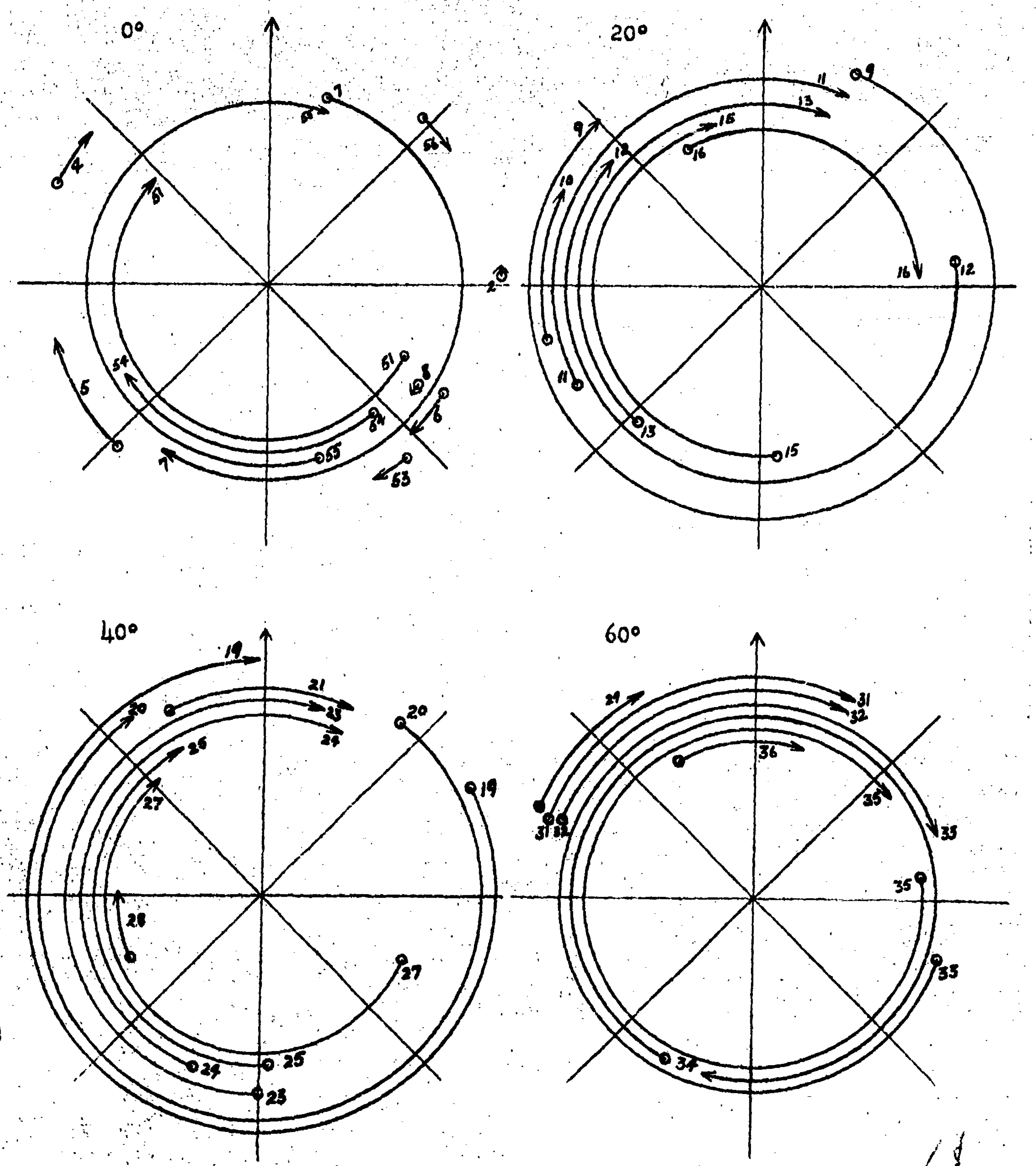


Figure 46

COURSE OF ORIENTATION THRU TIPPING SCREEN

1/16" Dural Screen Minimum Yaw Position

Caliber .30 M1922 A.P. Projectile

O = Entrance Orientation → = Exit Orientation

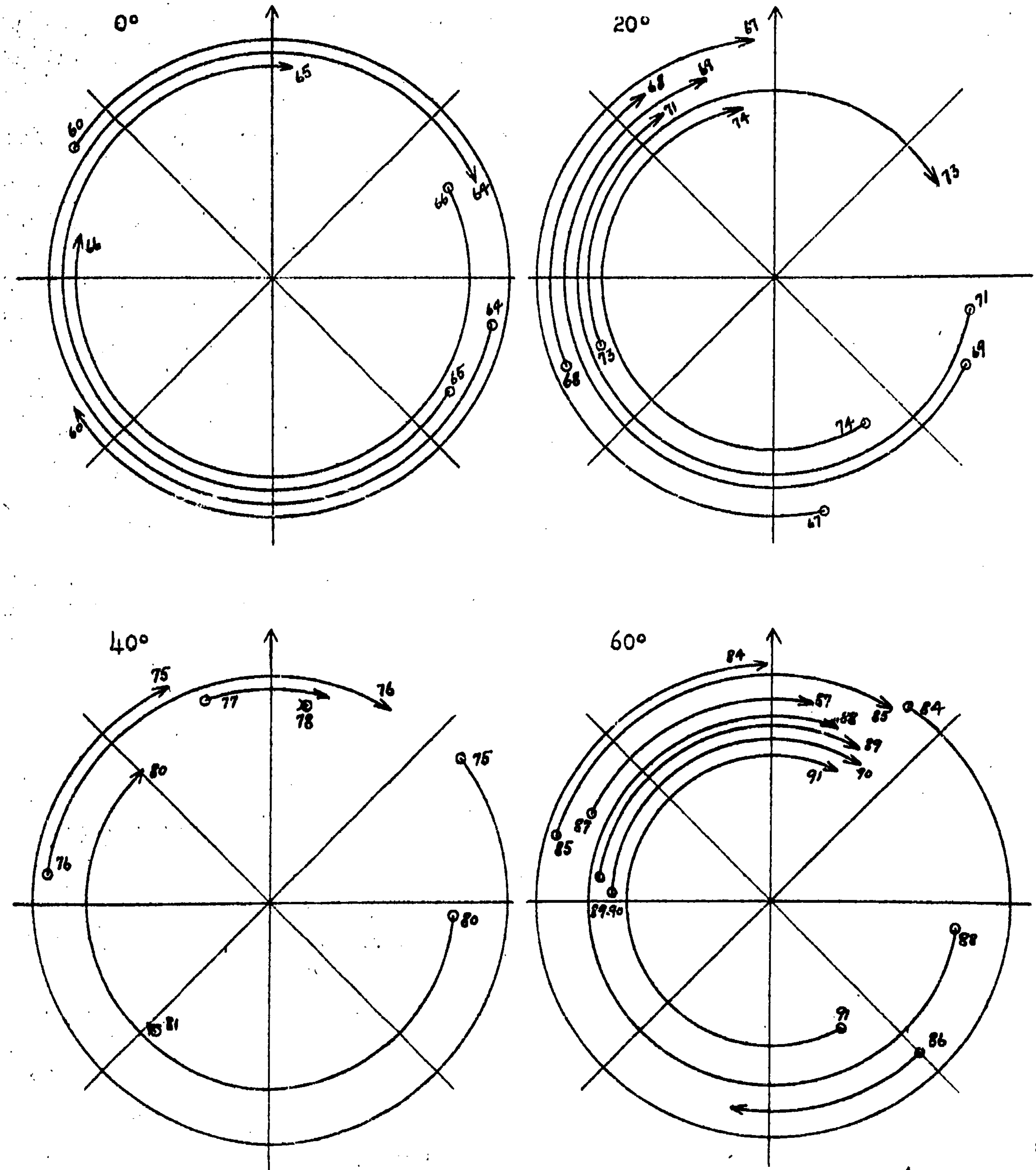


Figure 47

COURSE OF ORIENTATION THRU TIPPING SCREEN

1/8" Dural Screen

Minimum Yaw Position

Caliber .30 M1922 A.P. Projectile

⊙ = Entrance Orientation → = Exit Orientation

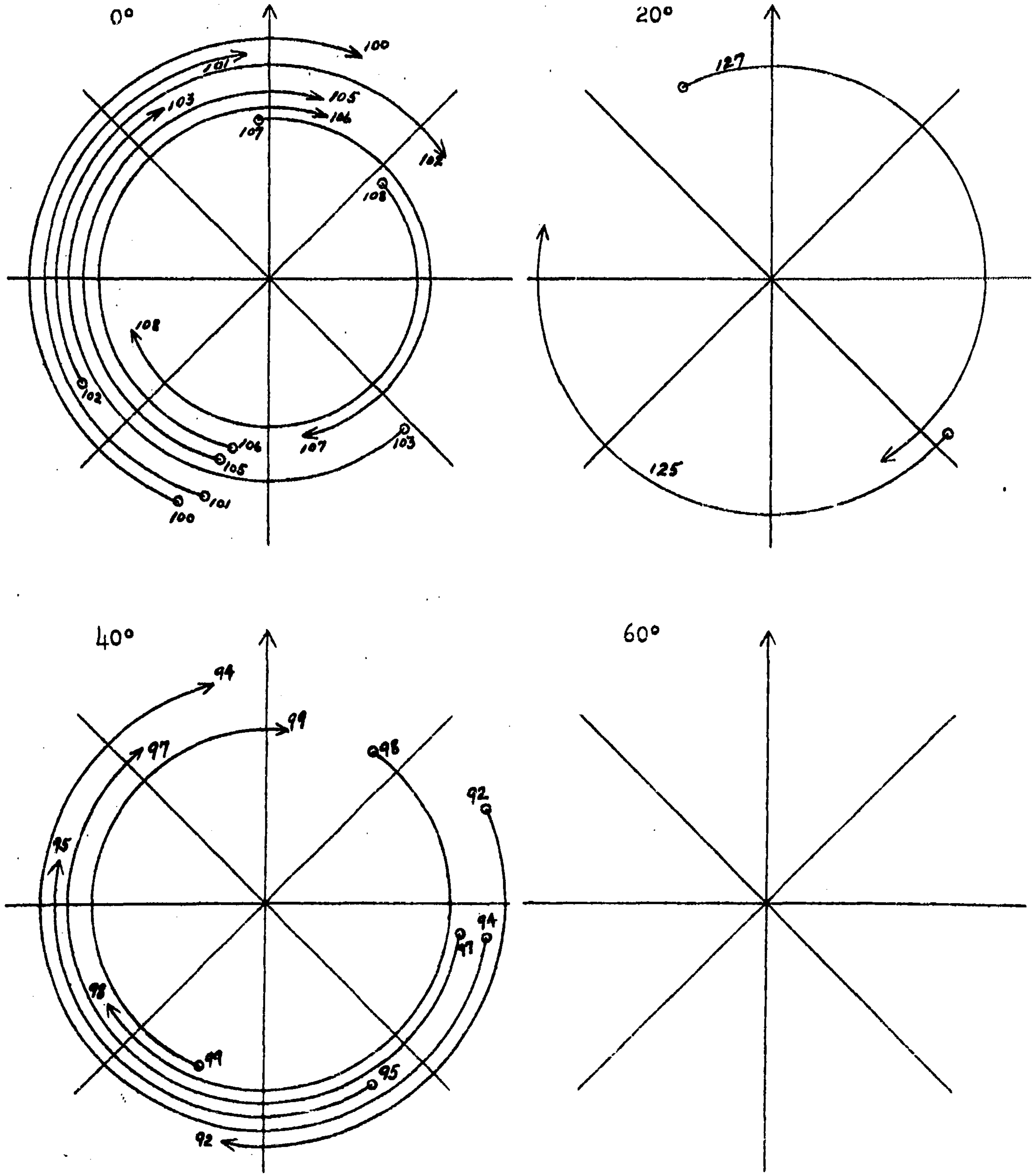


Figure 48

COURSE OF ORIENTATION THRU TIPPING SCREEN

1/8" Dural Screen | Minimum Yaw Position

Caliber .50 M1 A.P. Projectile

0 = Entrance Orientation | → = Exit Orientation

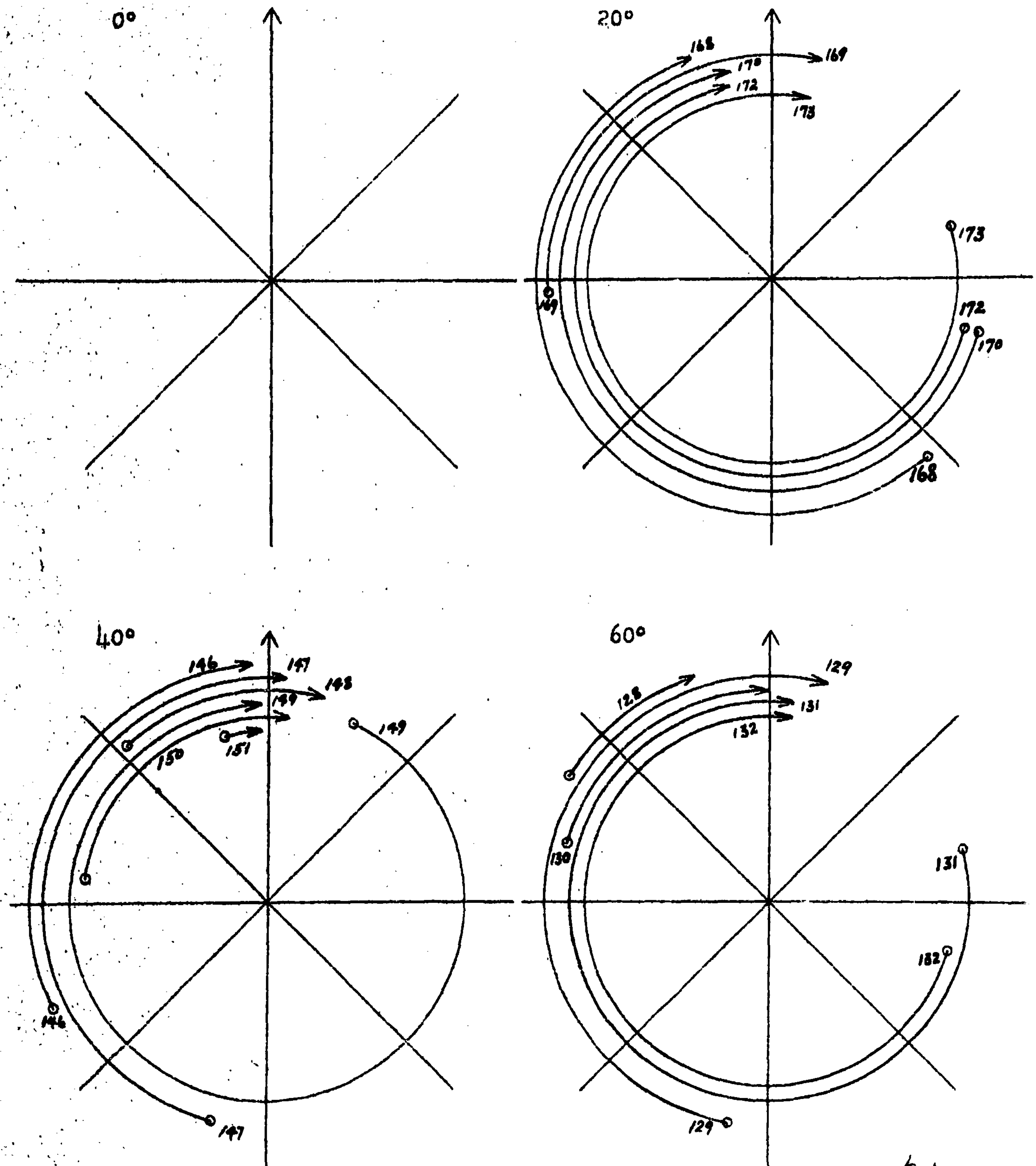
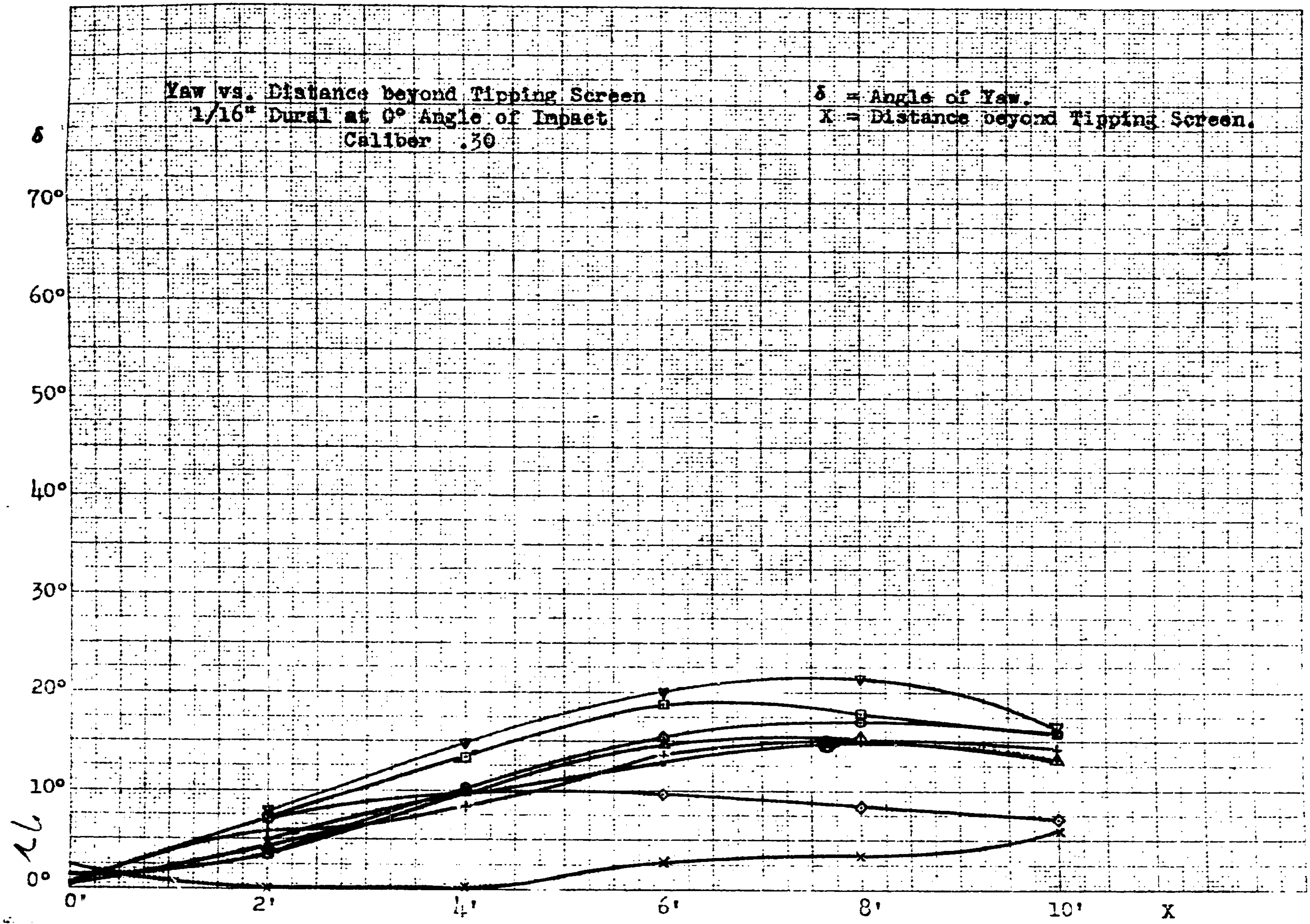


Figure 49

Figure 50


Yaw vs. Distance beyond Tipping Screen
1/16" Dural at 0° Angle of Impact
Caliber .30
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0"
2'
4'
6'
8'
10'
X

72

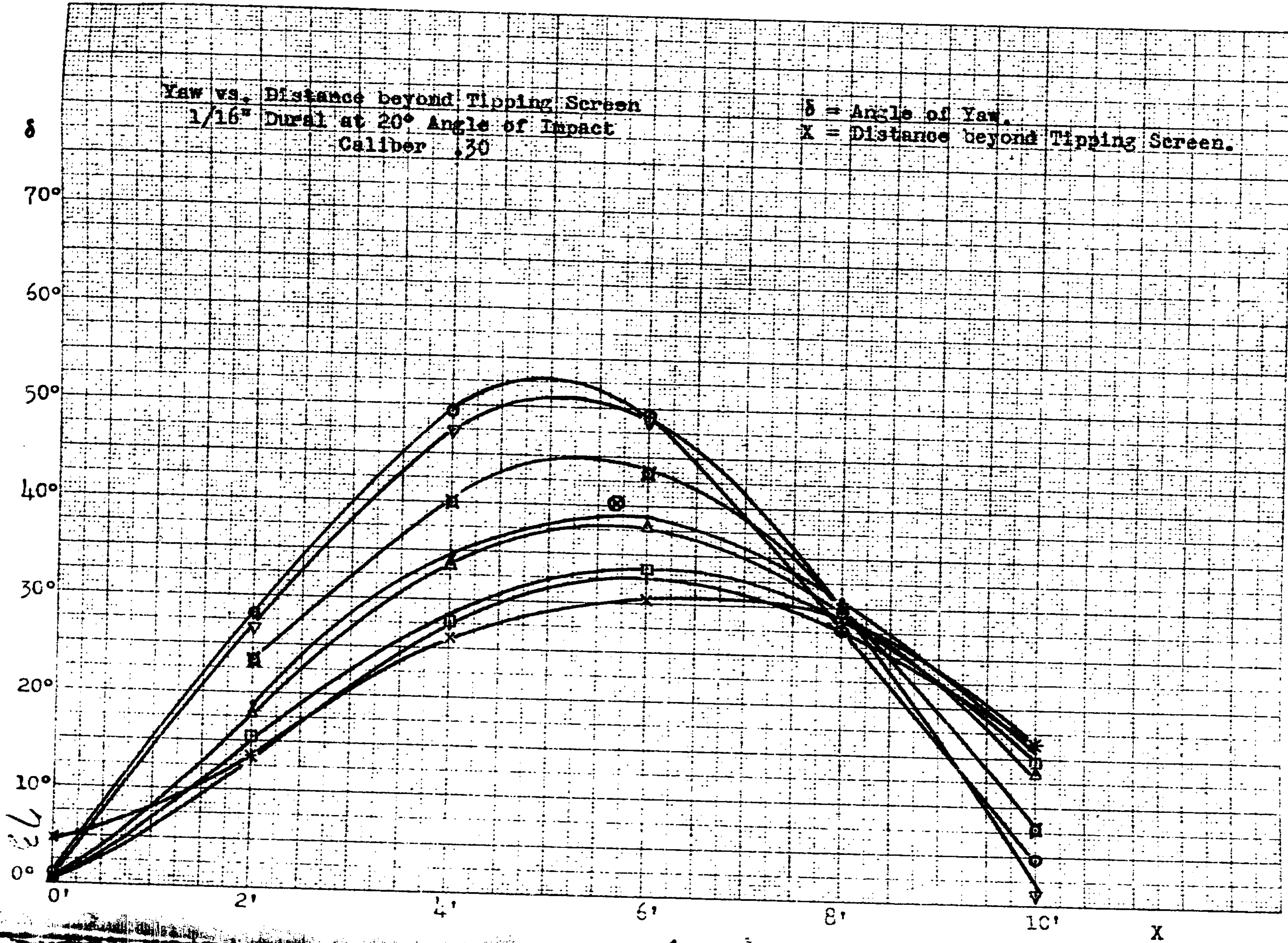

Yaw vs. Distance beyond Tipping Screen
1/16" Dural at 20° Angle of Impact
Caliber .30
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
X

Figure 51

Figure 52

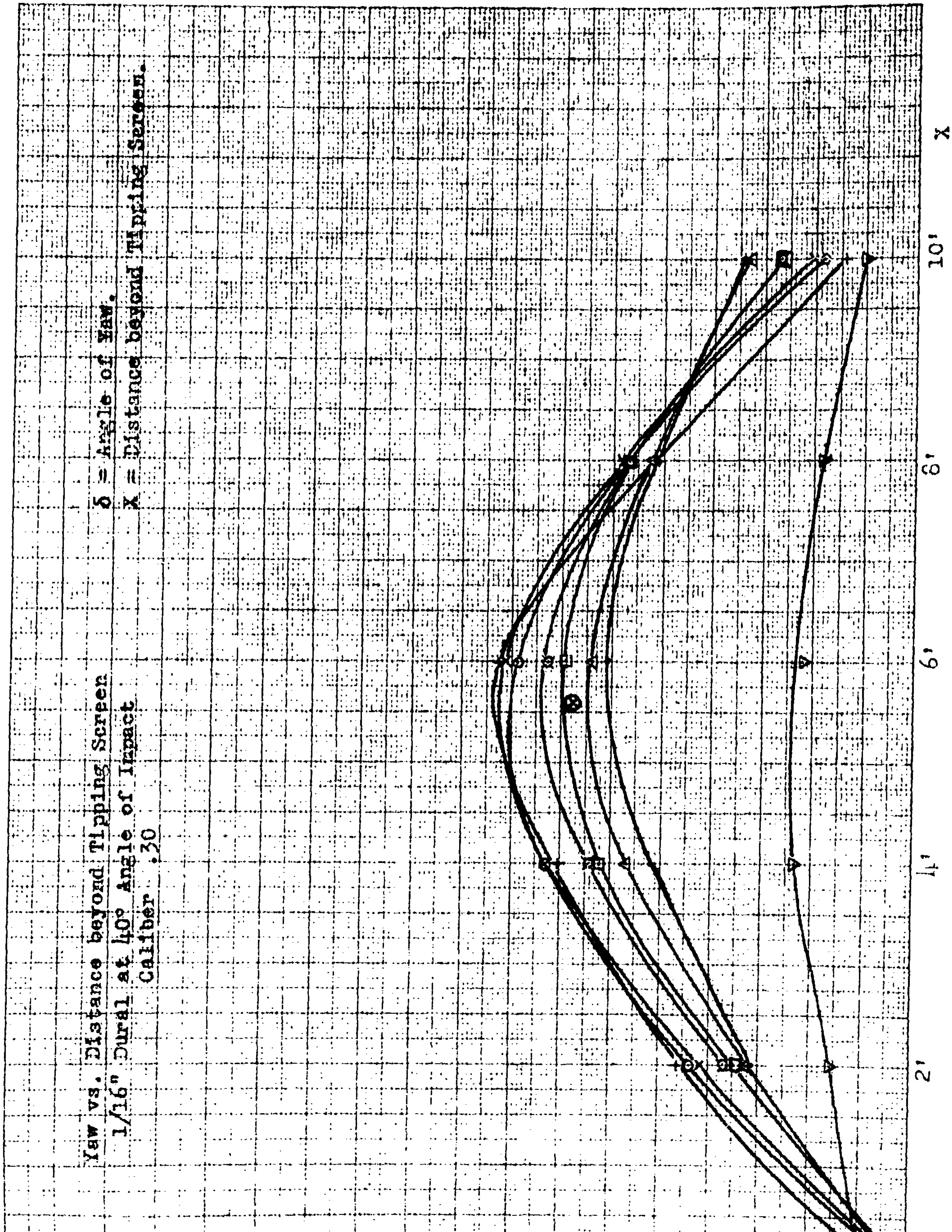
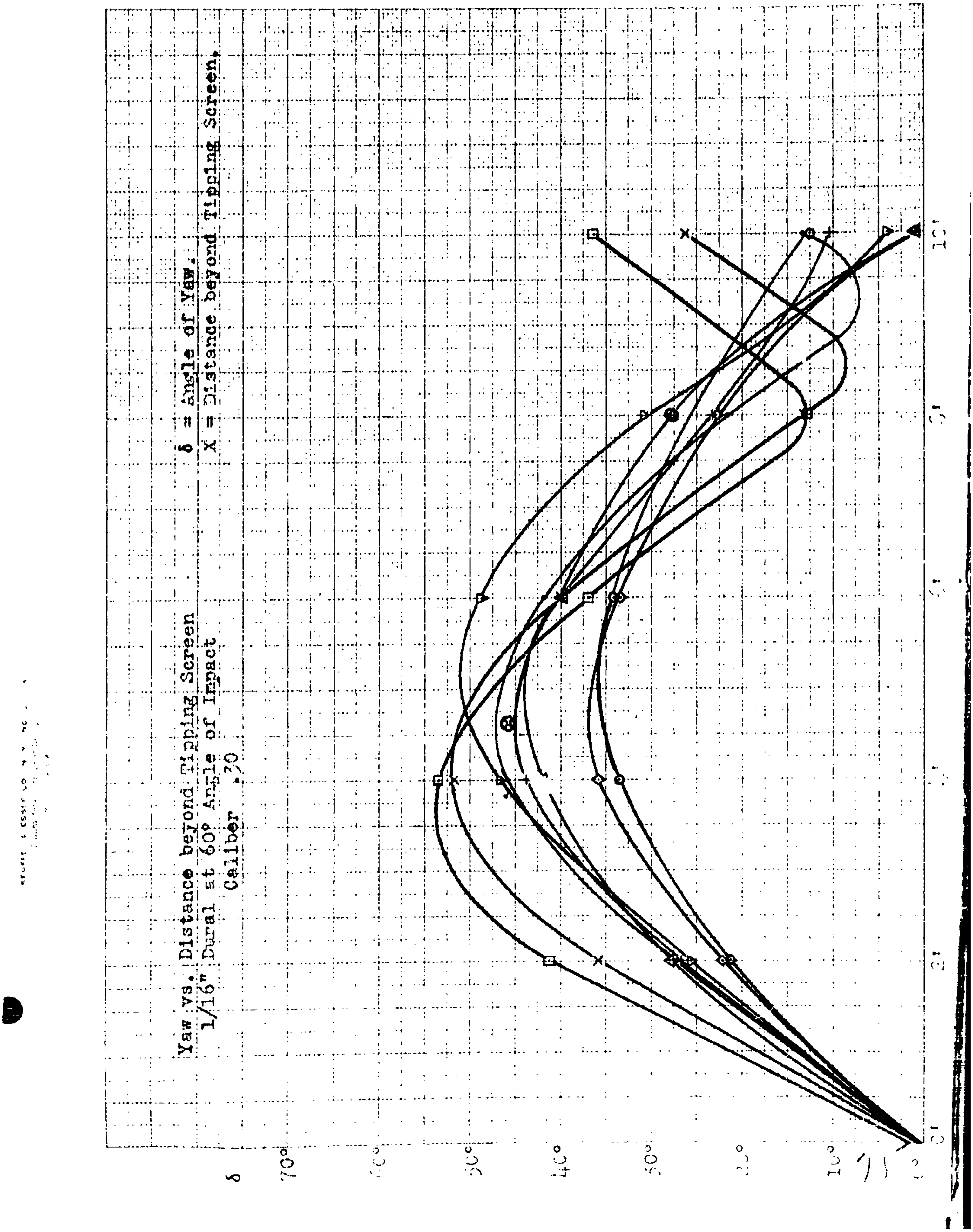

Yaw vs. Distance beyond Tipping Screen
1/16" Dural at 40° Angle of Impact
Caliber .30
δ = Angle of Yaw
X = Distance beyond Tipping Screen
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
X

Figure 53


Yaw vs. Distance beyond Tipping Screen
1/16" Dural at 60° Angle of Impact
Caliber .30
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
50°
40°
10°

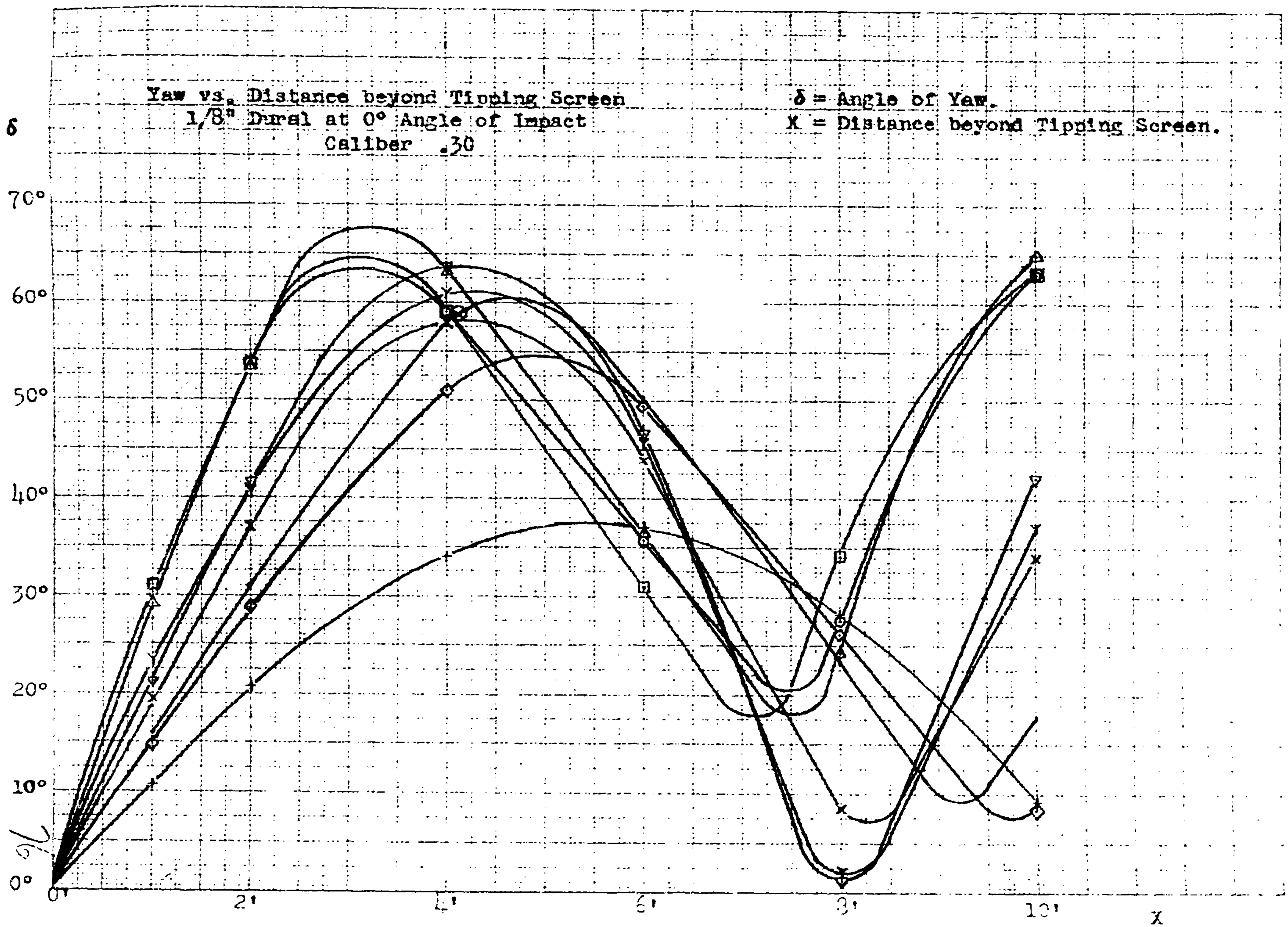
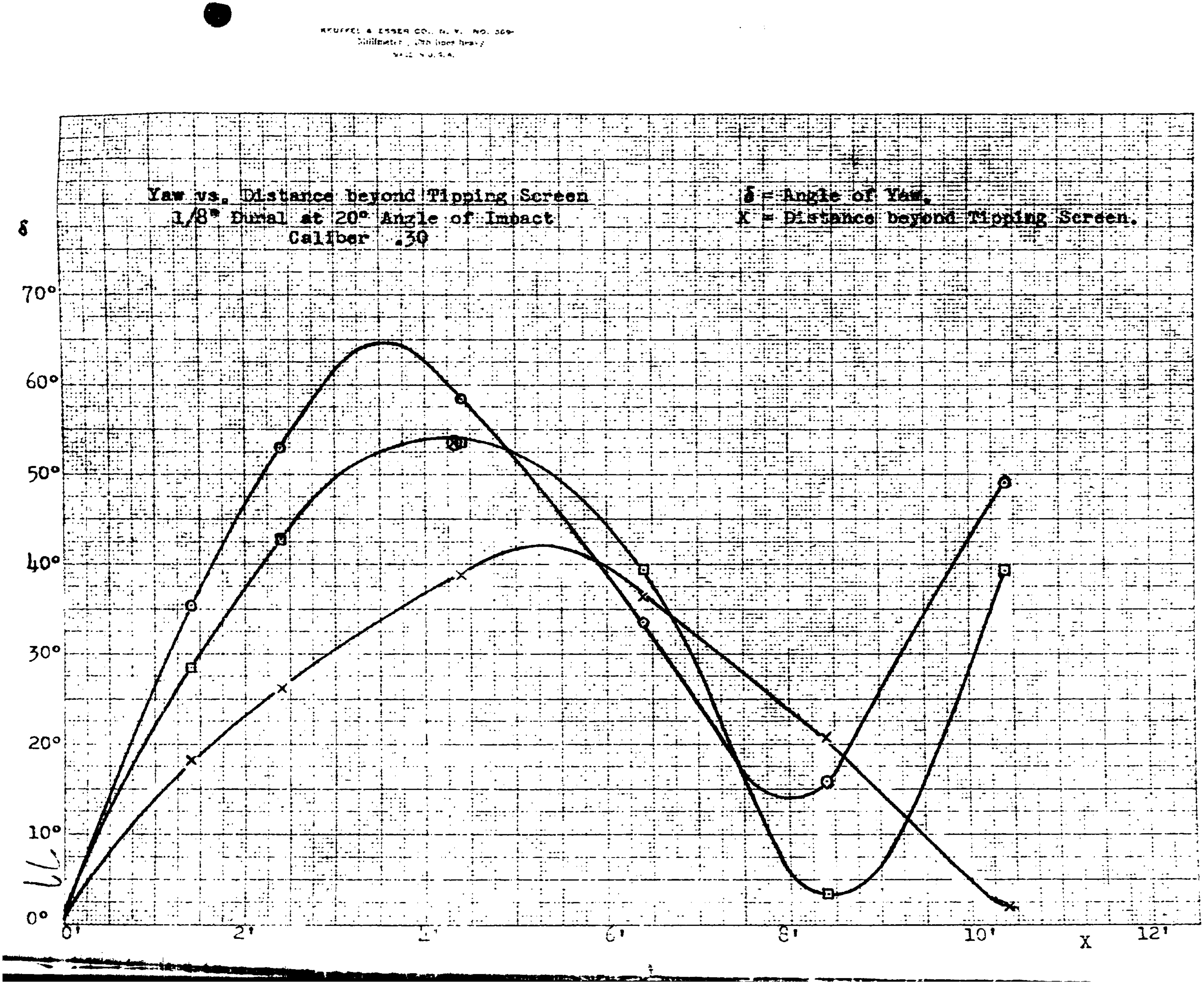

Yaw vs. Distance beyond Tipping Screen
1/8" Dural at 0° Angle of Impact
Caliber .30
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
X

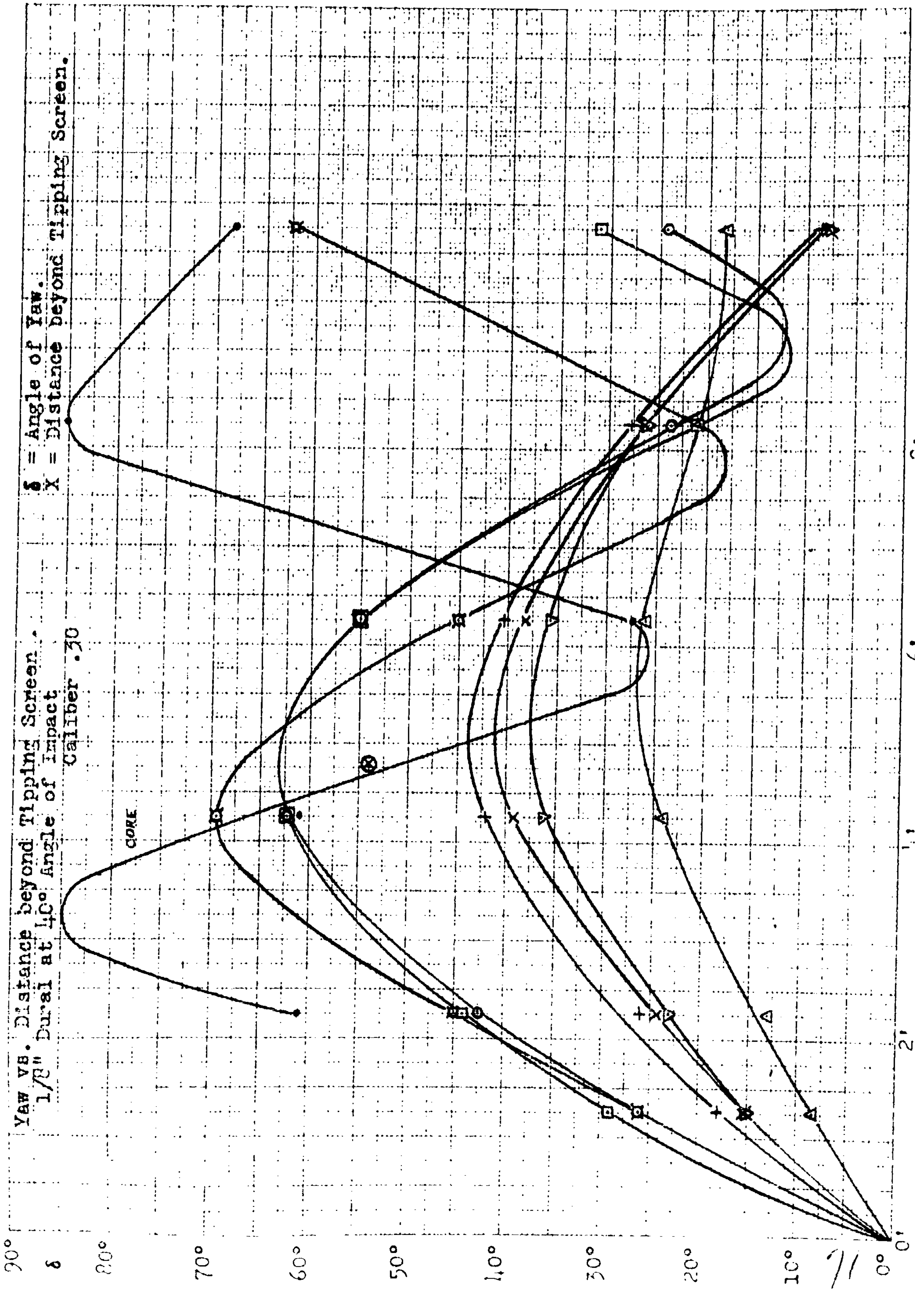
Figure 5.



KEUFFEL & ESSER CO., N. Y. NO. 359-
Yaw vs. Distance beyond Tipping Screen
1/8" Dural at 20° Angle of Impact
Caliber .30
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
12'
X
77

Figure 55

Figure 56



Yaw vs. Distance beyond Tipping Screen.
1/8" Dural at 40° Angle of Impact
Caliber .30
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
CORE
90°
δ
80°
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
12'
X

71

Figure 57

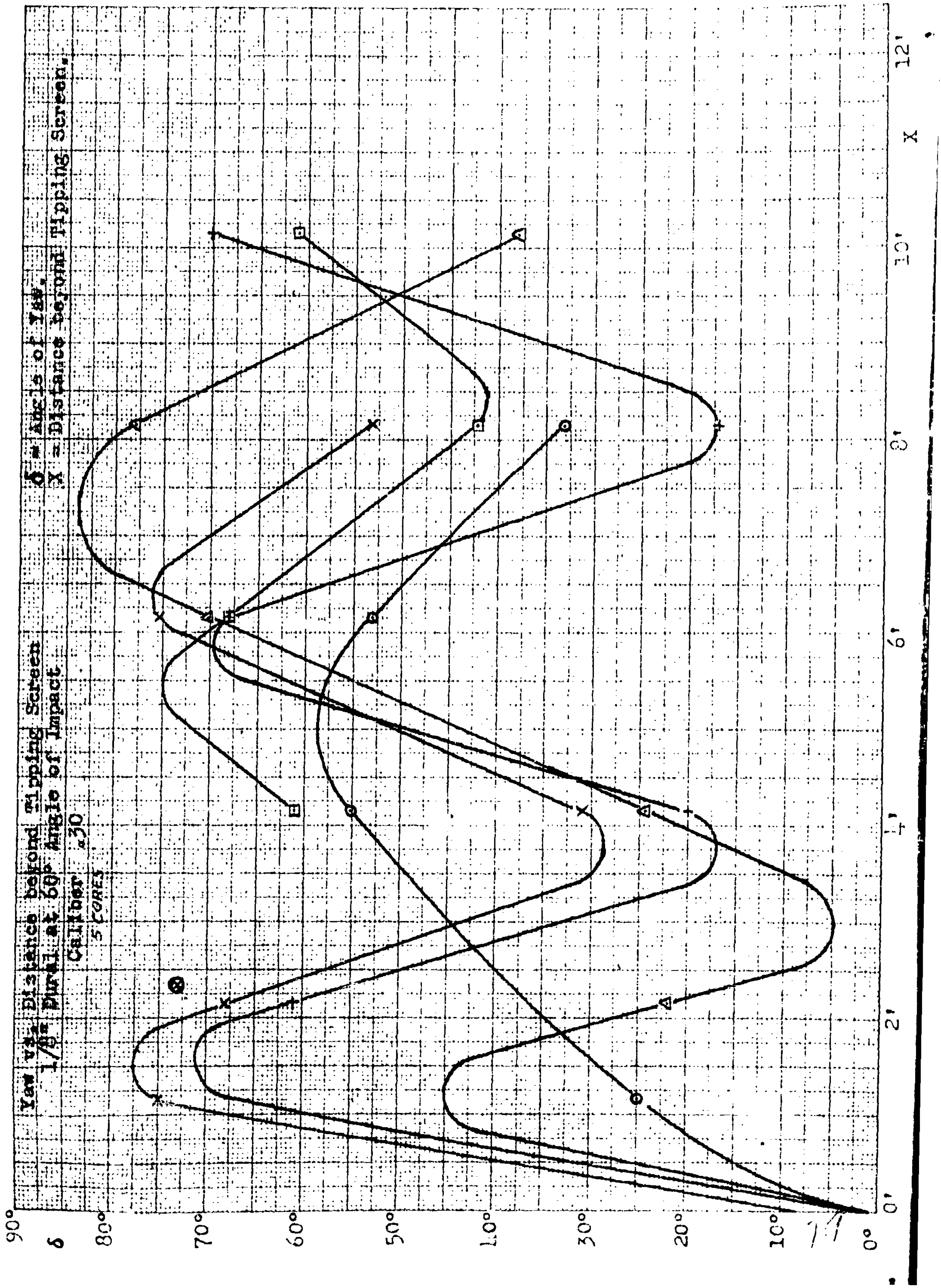

Yaw vs. Distance beyond Tipping Screen
1/8" Dural at 60° Angle of Impact
Caliber .30
5 CORES
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
90°
δ
80°
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
12'
X

Figure 58

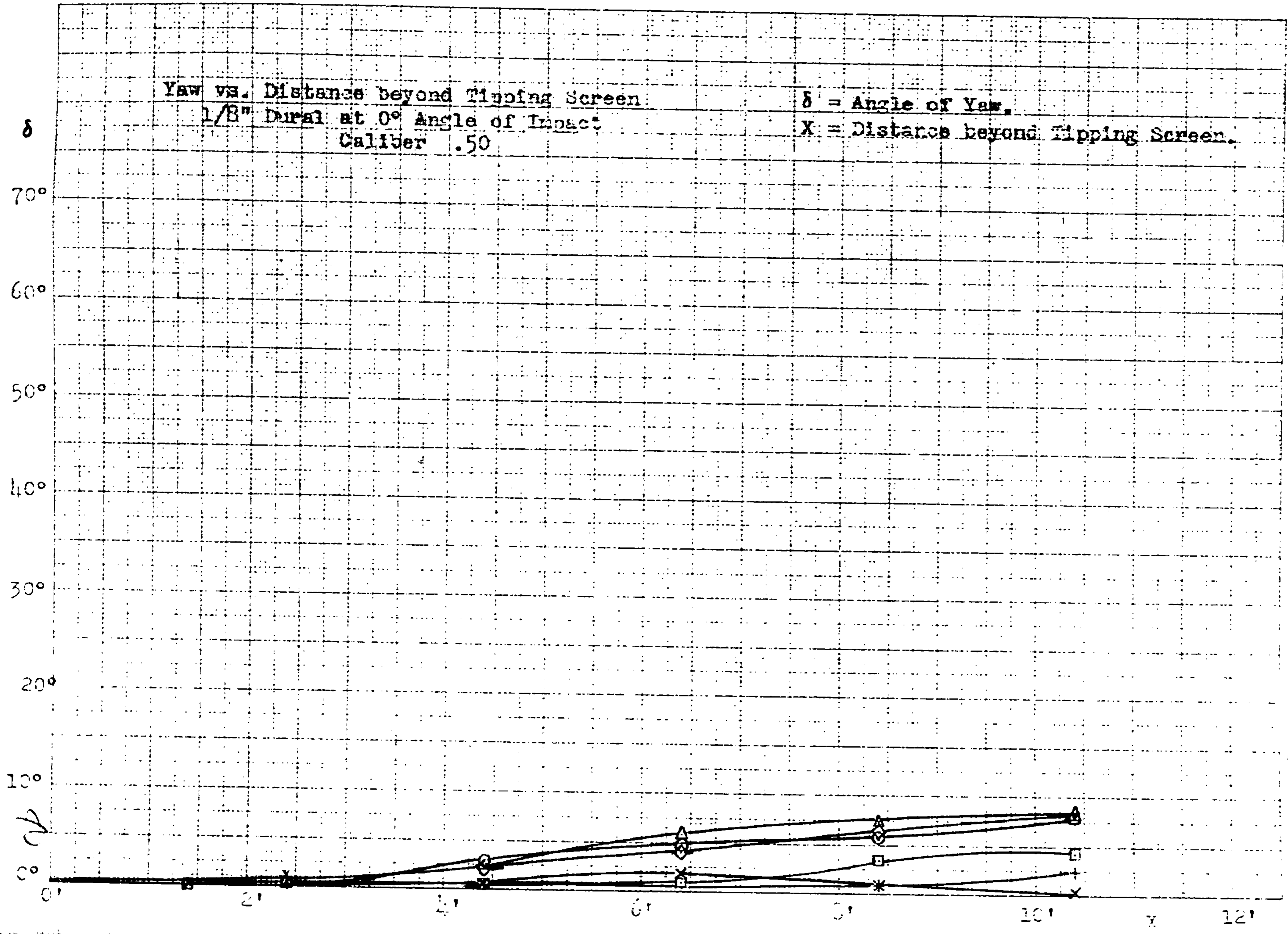
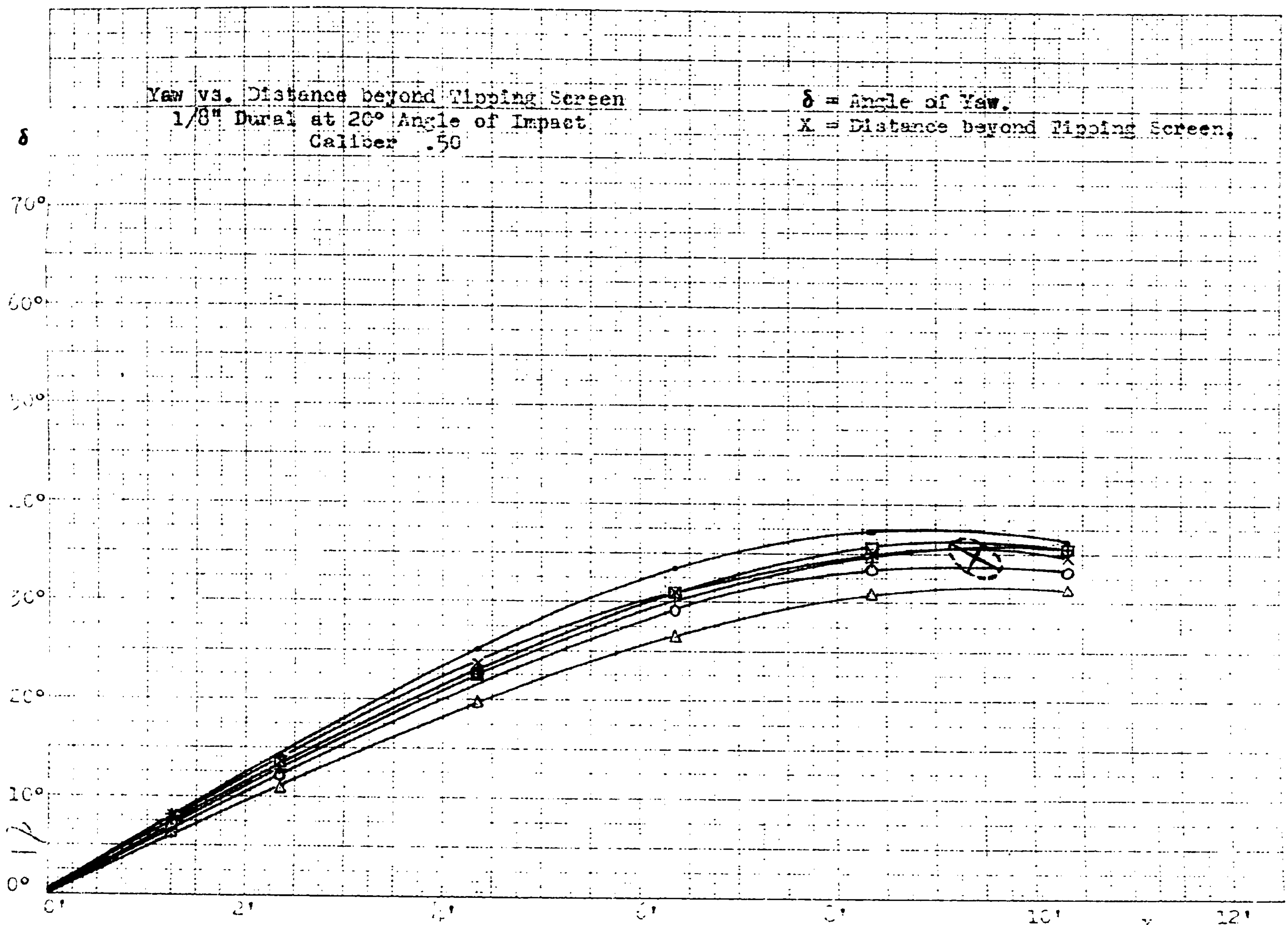

Yaw vs. Distance beyond Tipping Screen
1/8" Dural at 0° Angle of Impact
Caliber .50
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
X
12'

Figure 59


Yaw vs. Distance beyond Tipping Screen
1/8" Dural at 20° Angle of Impact
Caliber .50
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
12'
X

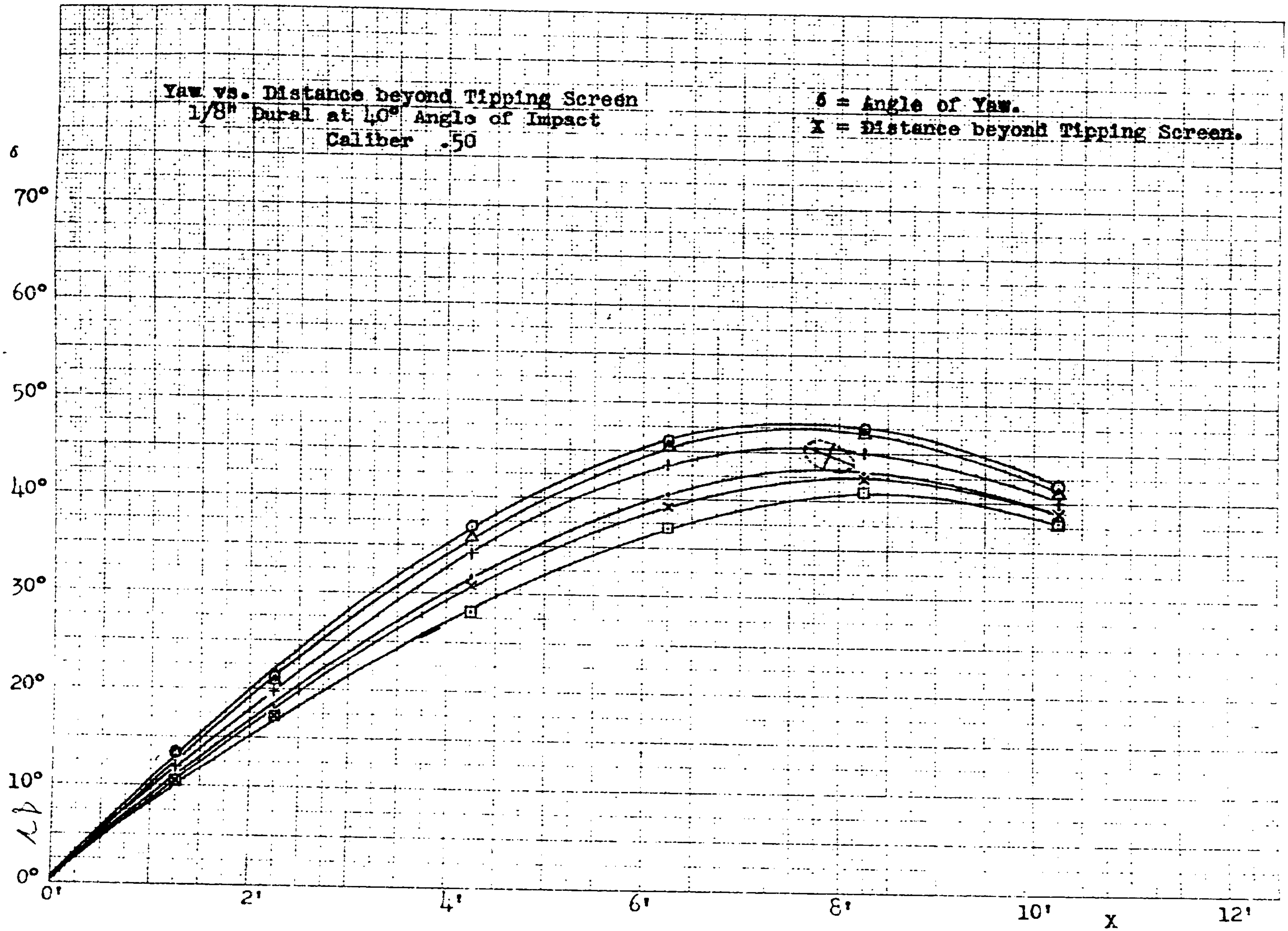
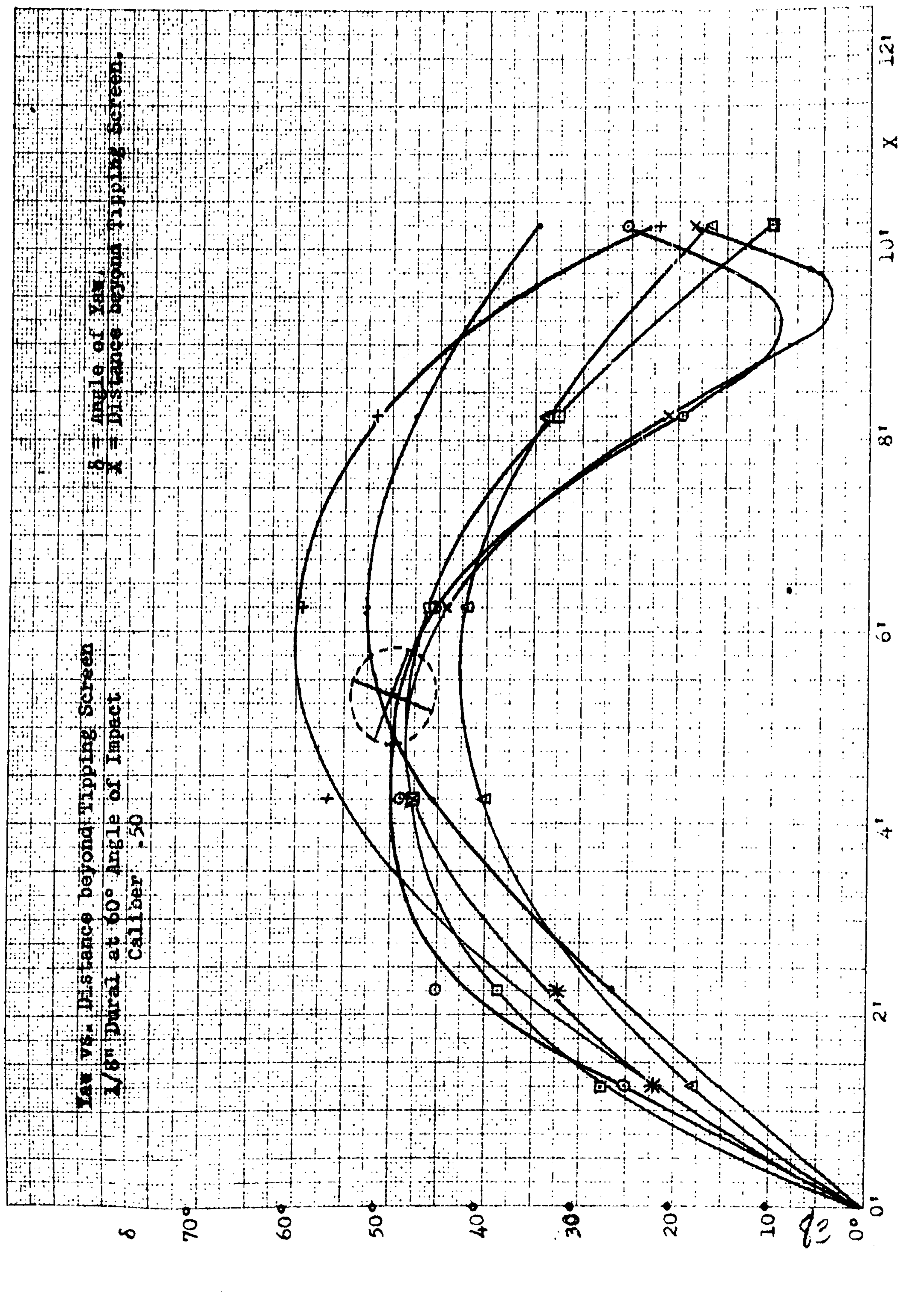
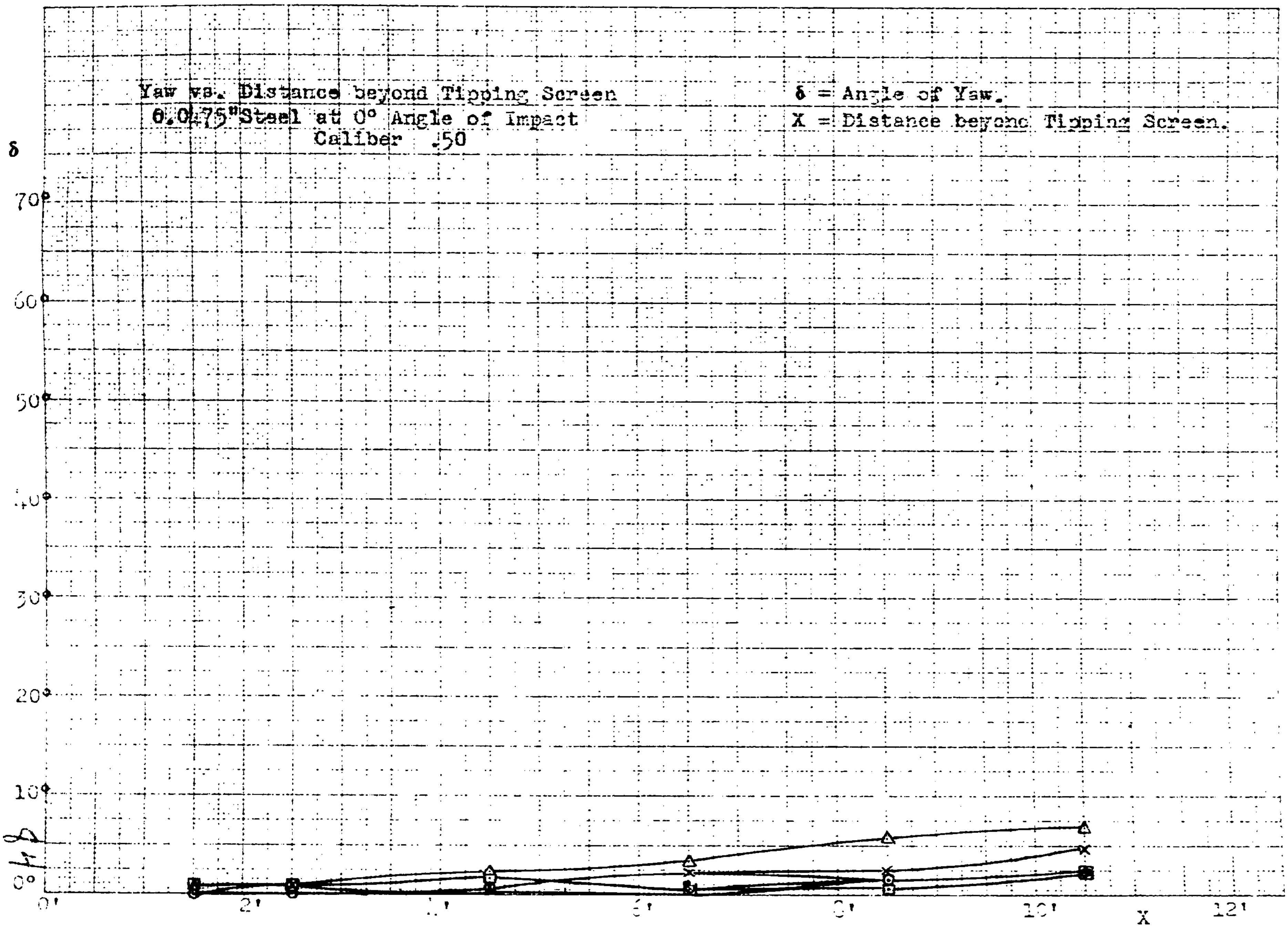

Yaw vs. Distance beyond Tipping Screen
1/8" Dural at 40° Angle of Impact
Caliber .50
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
12'
X

Figure 60

Figure 61


Yaw vs. Distance beyond Tipping Screen
1/8" Dural at 60° Angle of Impact
Caliber .50
δ = Angle of Yaw
X = Distance beyond Tipping Screen
δ
70°
60
50
40
30
20
10
0°
0'
2'
4'
6'
8'
10'
12'
X



Yaw vs. Distance beyond Tipping Screen
0.0475" Steel at 0° Angle of Impact
Caliber .50
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
12'
X

Figure 62

Figure 63

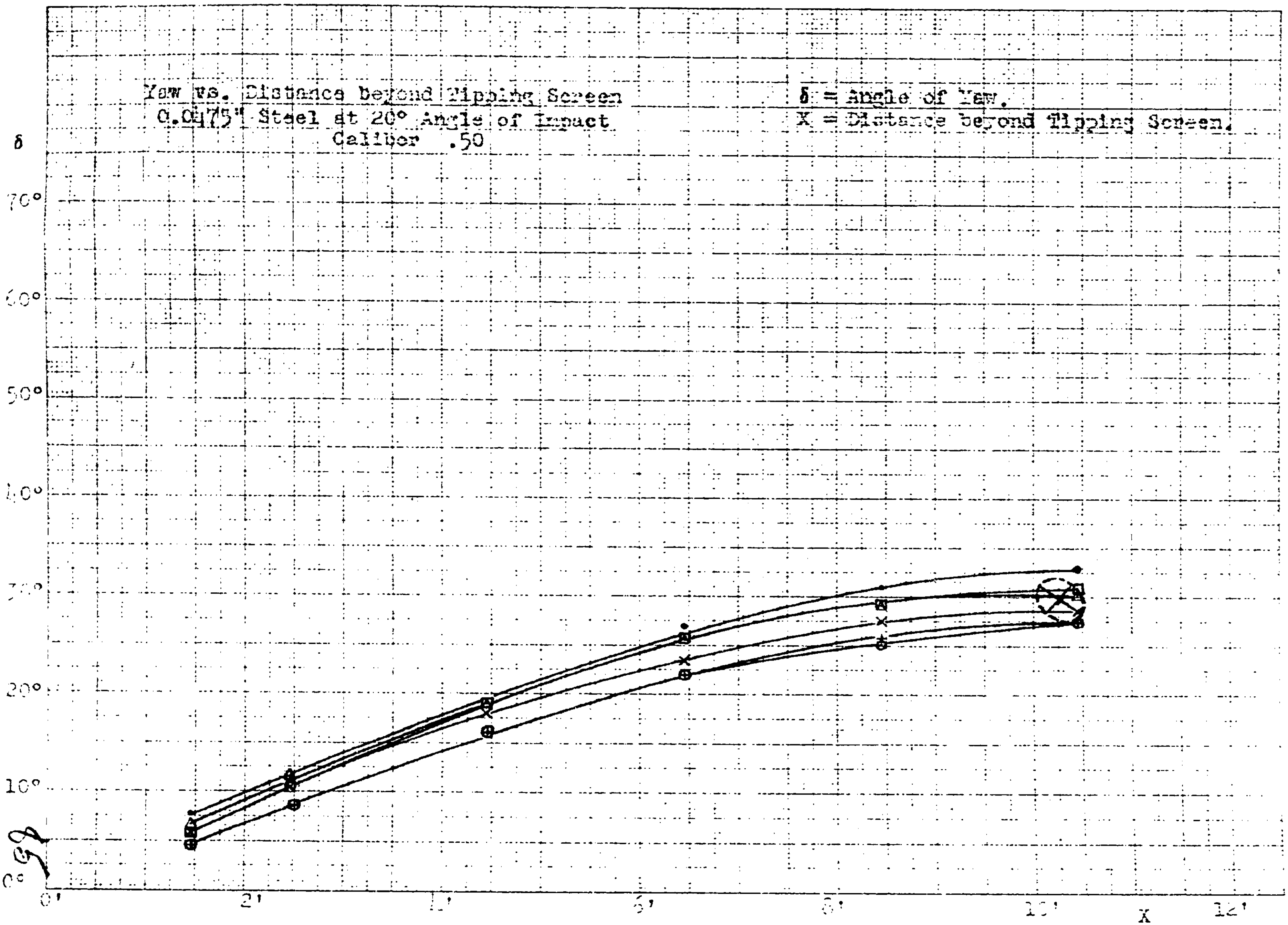

Yaw vs. Distance beyond Tipping Screen
0.0475" Steel at 20° Angle of Impact
Caliber .50
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
X
12'

Figure 64

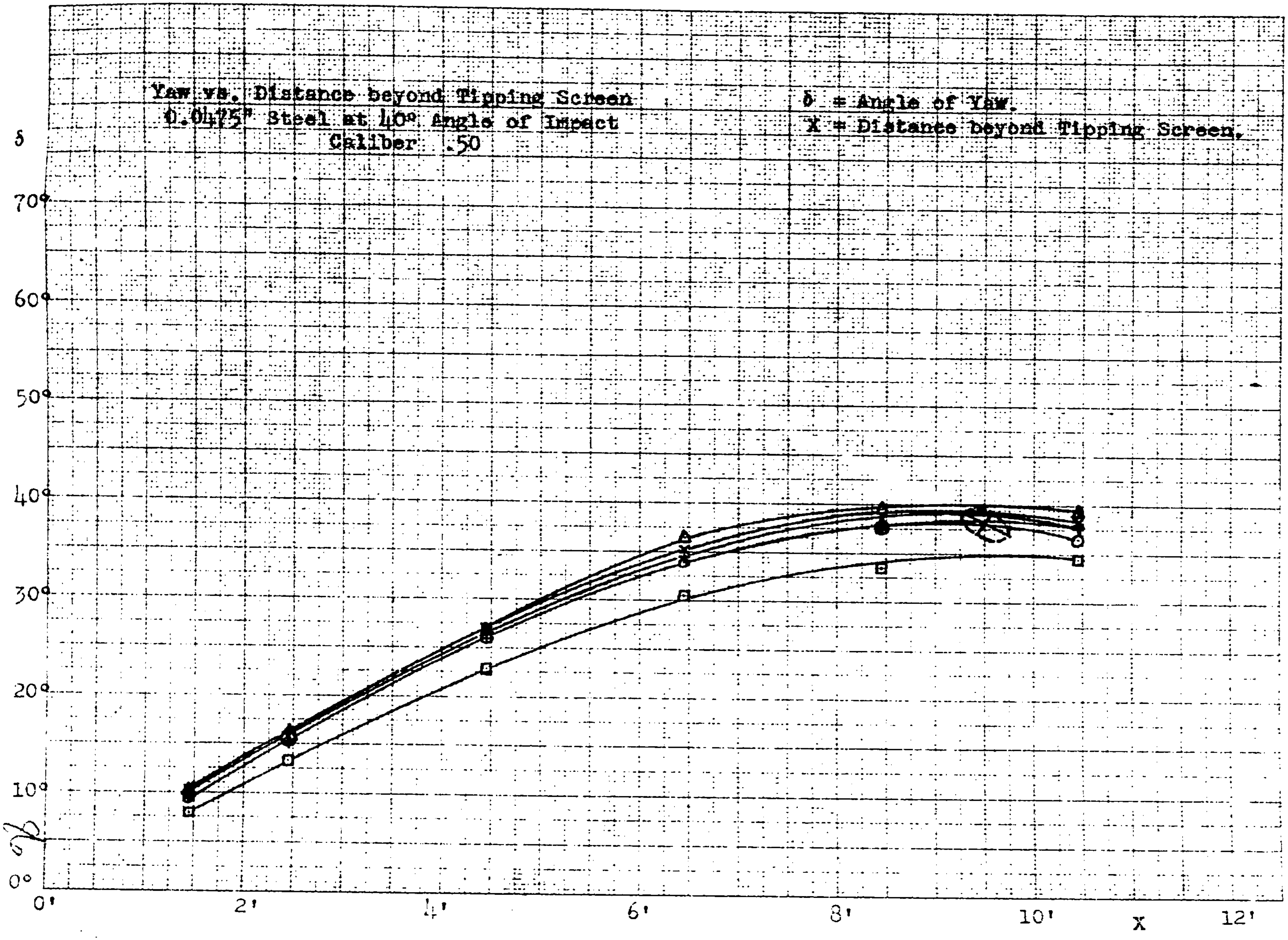

Yaw vs. Distance beyond Tipping Screen
0.0475" Steel at 40° Angle of Impact
Caliber .50
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
12'
X

Figure 65

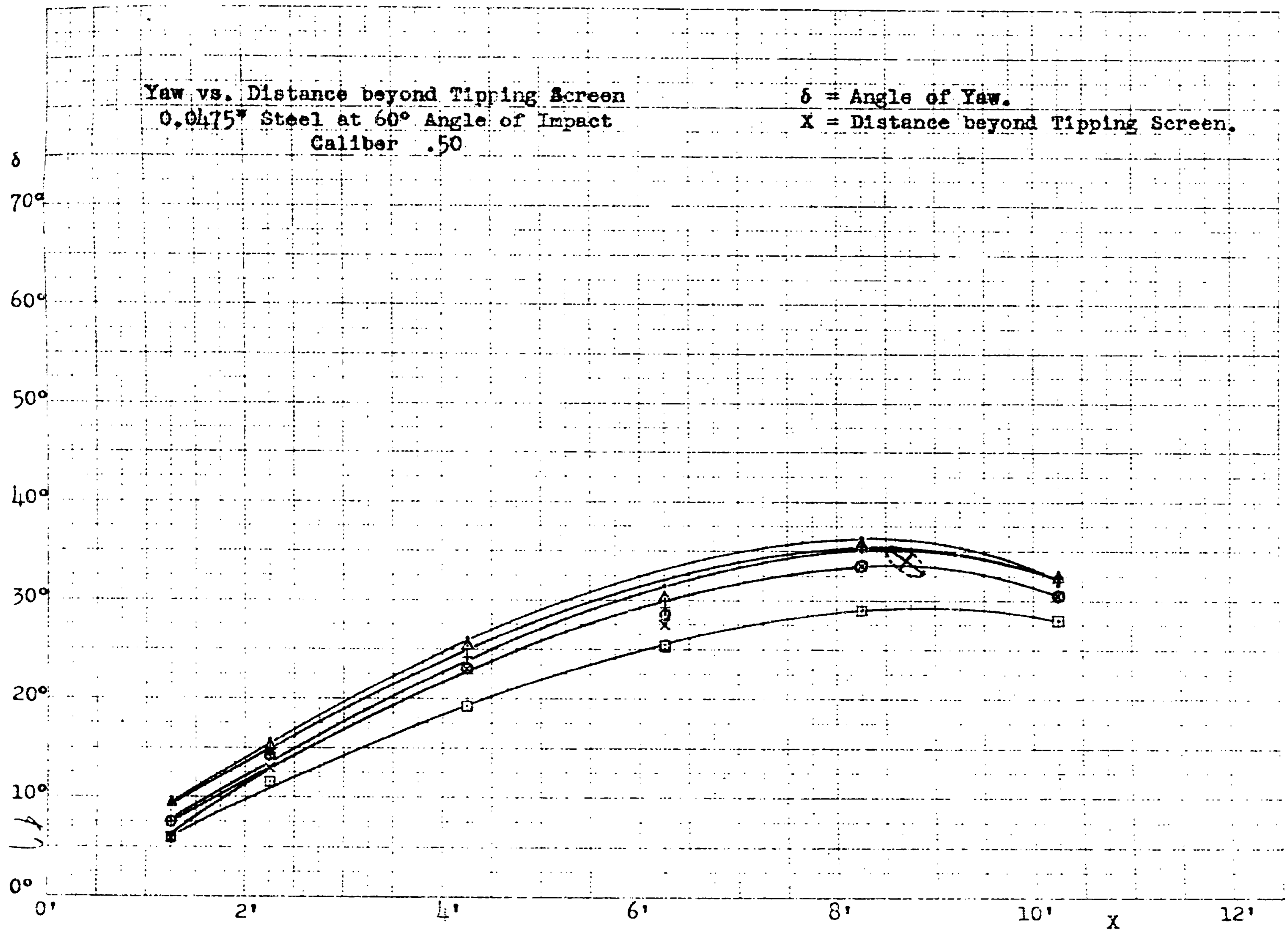
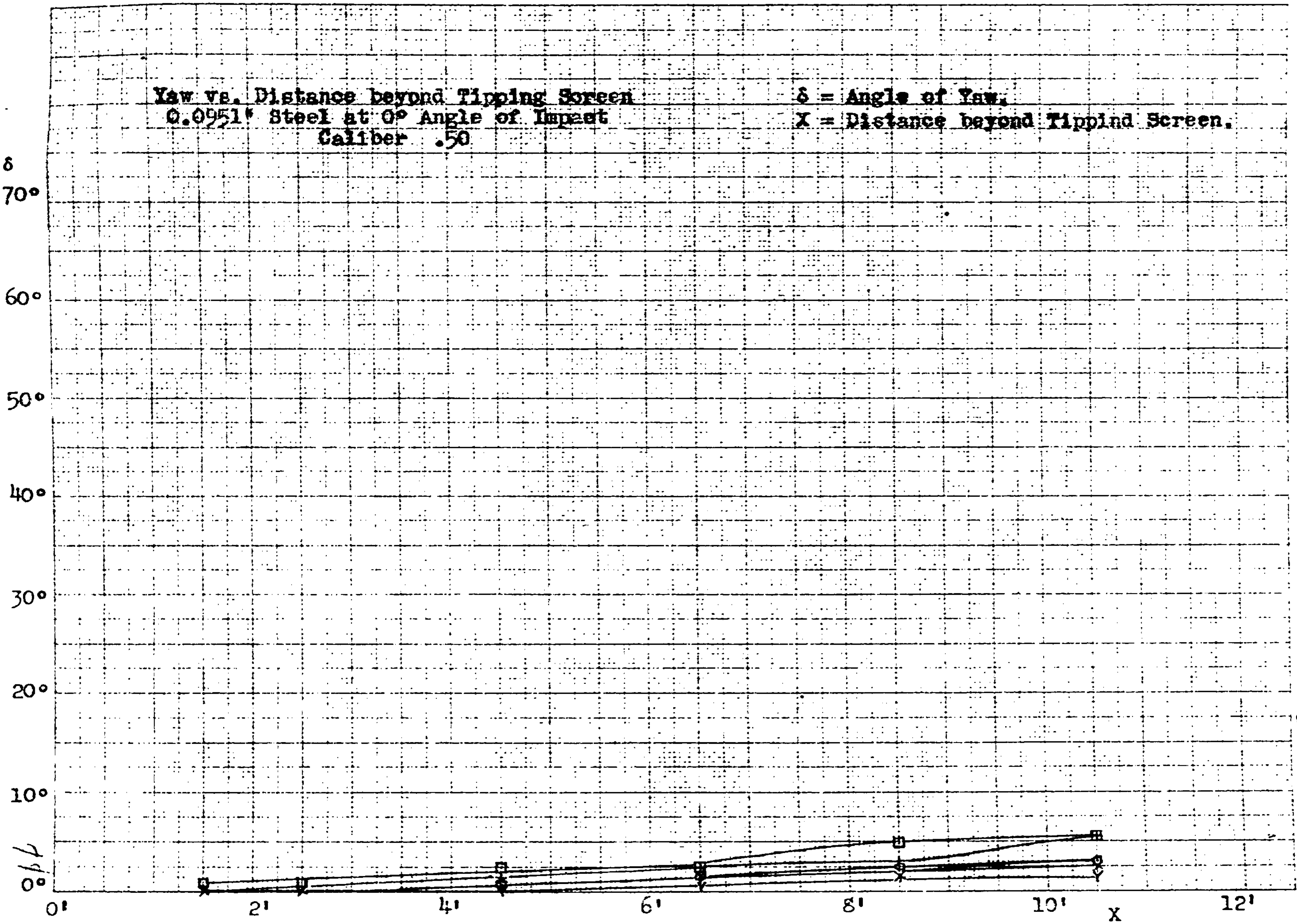
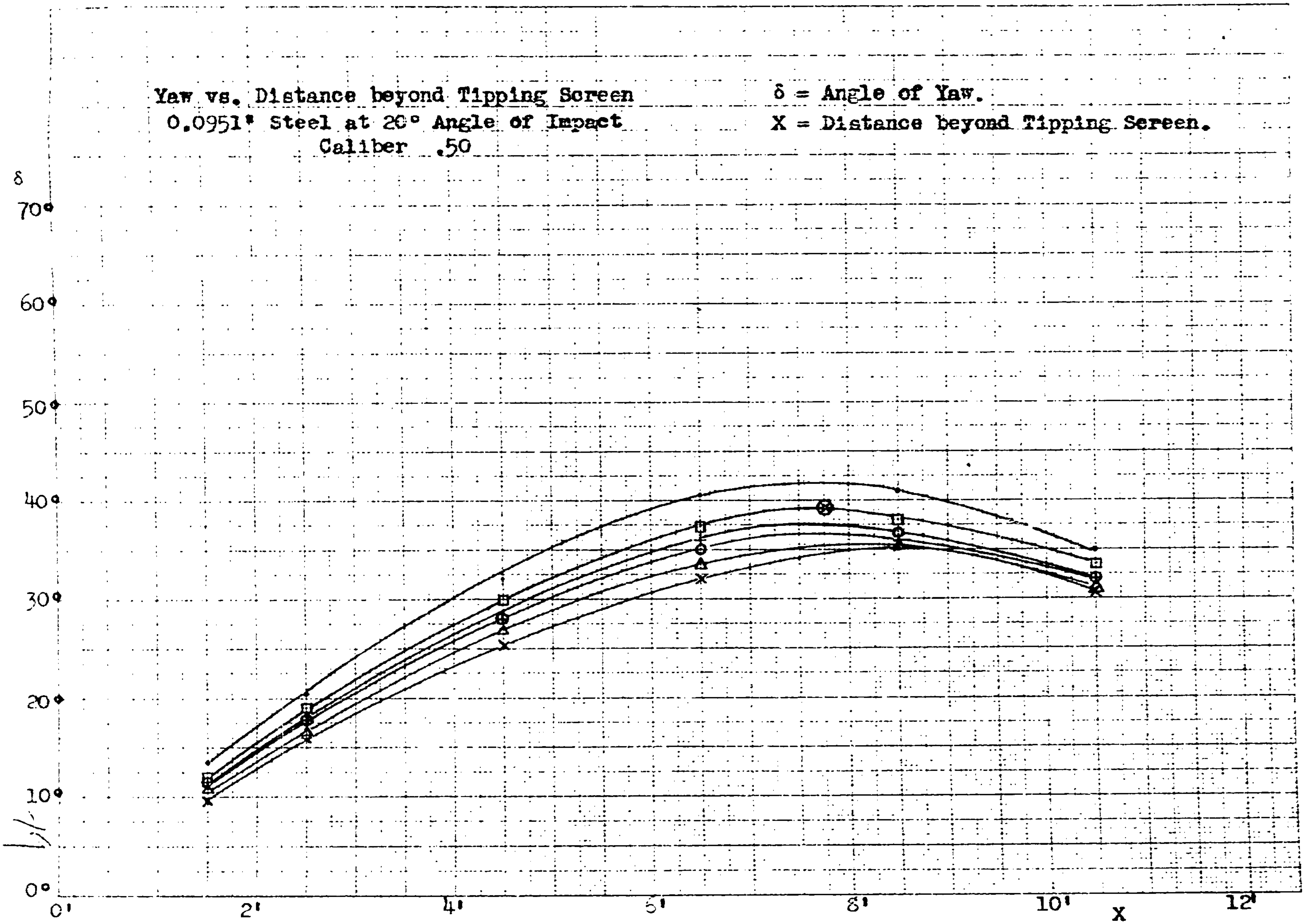

Yaw vs. Distance beyond Tipping Screen
0.0475" Steel at 60° Angle of Impact
Caliber .50
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
12'
X

Figure 66



114

Figure 67



Yaw vs. Distance beyond Tipping Screen
0.0951" Steel at 20° Angle of Impact
Caliber .50
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
12'
X

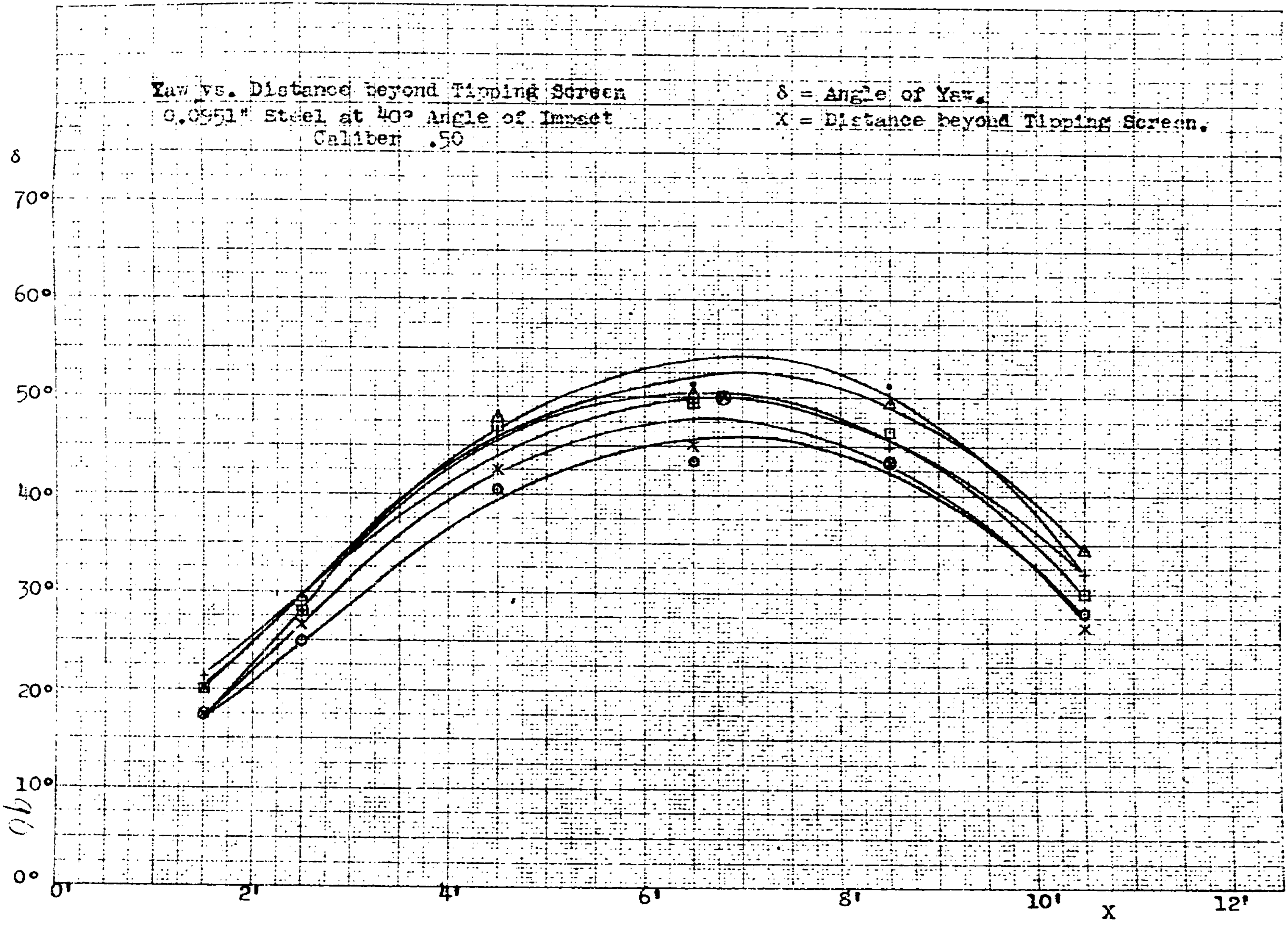
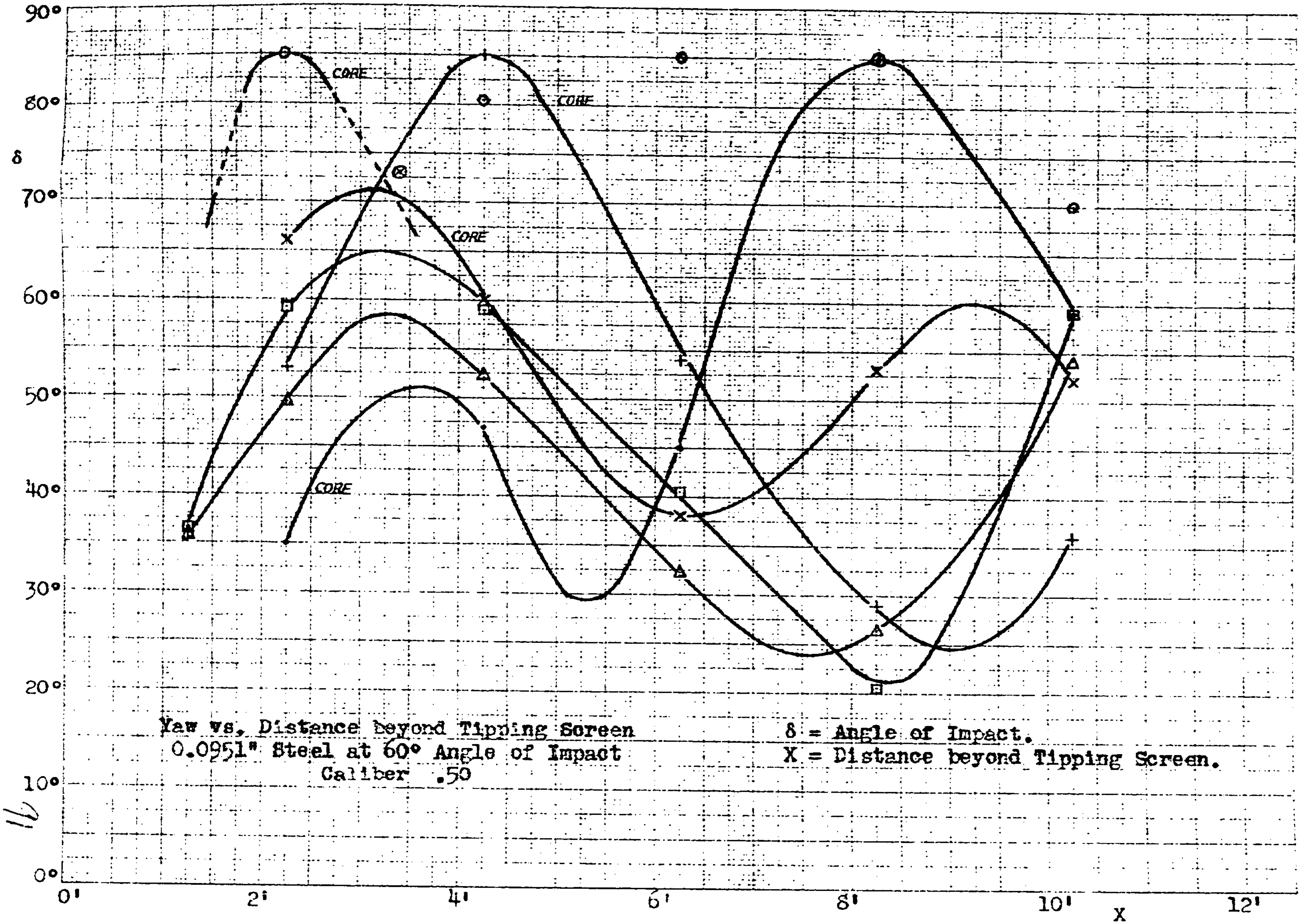

Yaw vs. Distance beyond Tipping Screen
0.0551" Steel at 40° Angle of Impact
Caliber .50
δ = Angle of Yaw.
X = Distance beyond Tipping Screen.
δ
70°
60°
50°
40°
30°
20°
10°
0°
0'
2'
4'
6'
8'
10'
12'
X

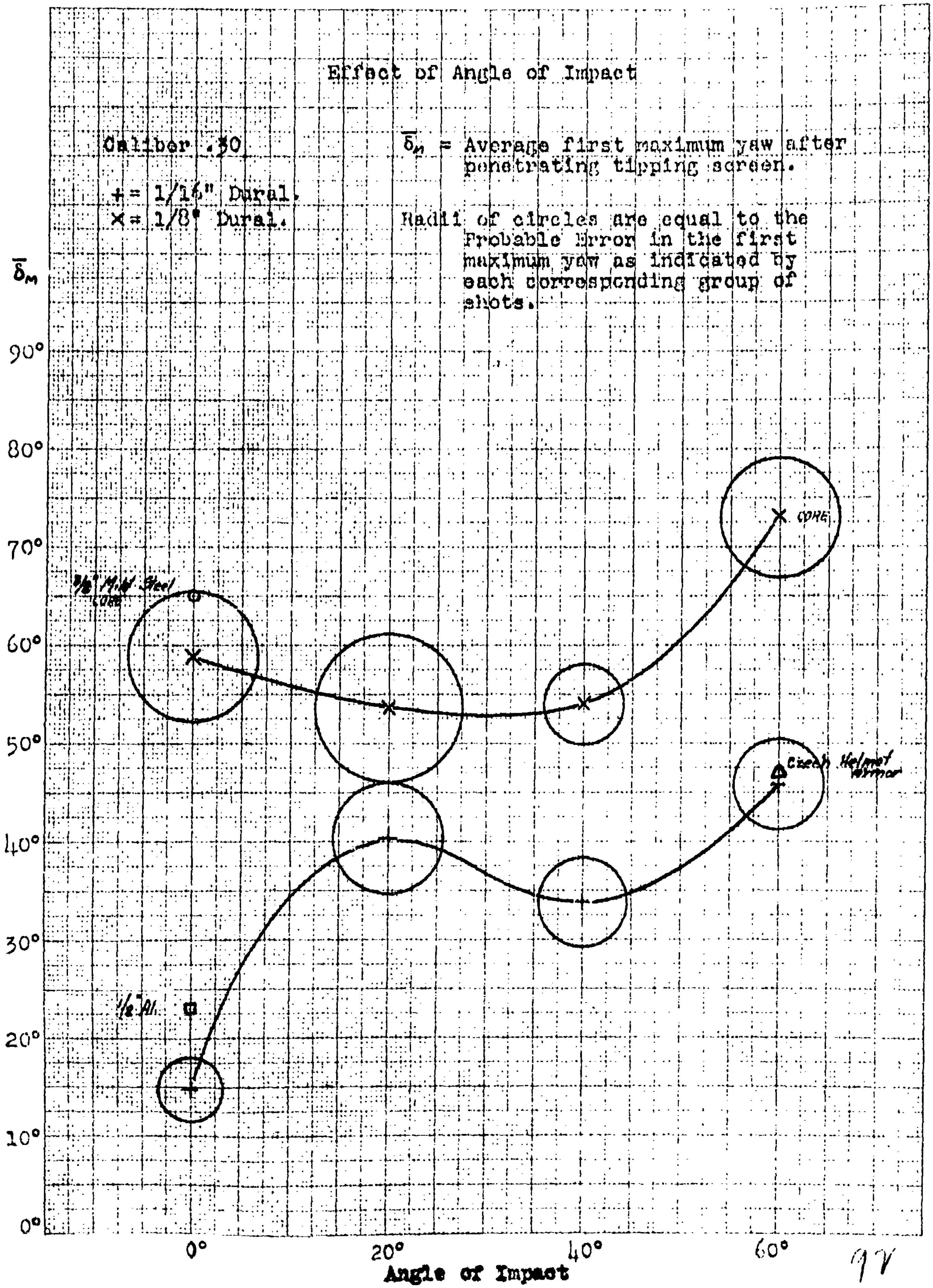
Figure 69



Yaw vs. Distance beyond Tipping Screen
0.0951" Steel at 60° Angle of Impact
Caliber .50

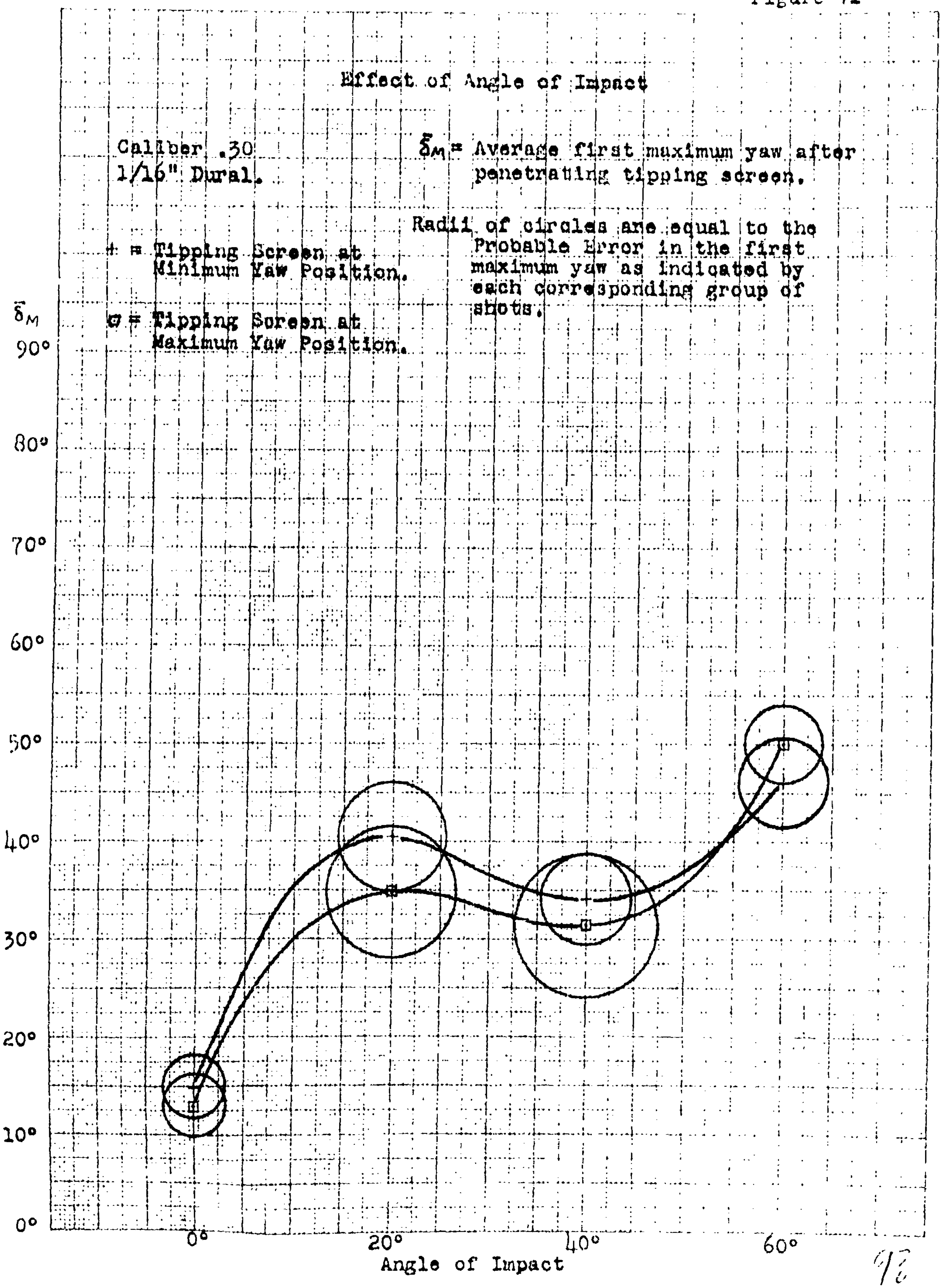
δ = Angle of Impact.
X = Distance beyond Tipping Screen.

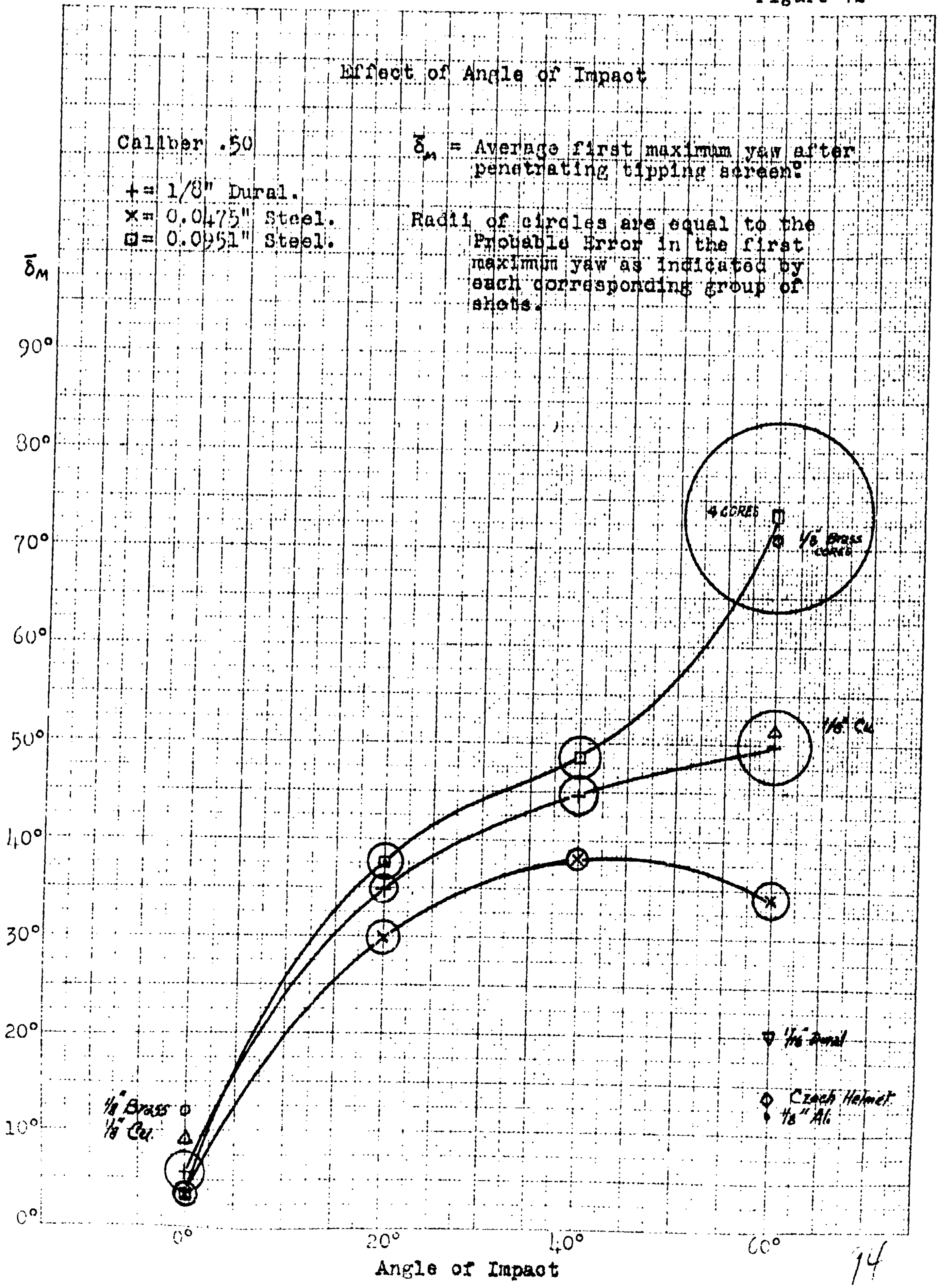
Figure 70



Effect of Angle of Impact
Caliber .30
+ = 1/16" Dural.
× = 1/8" Dural.
$\bar{\delta}_M$ = Average first maximum yaw after penetrating tipping screen.
Radii of circles are equal to the Probable Error in the first maximum yaw as indicated by each corresponding group of shots.
$\bar{\delta}_M$
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
3/8" Mild Steel core
core
Czech Helmet Armor
1/2" Al.
0°
20°
40°
60°
Angle of Impact

Figure 71


Effect of Angle of Impact
Caliber .30
1/16" Dural.
$\bar{\delta}_M$ = Average first maximum yaw after penetrating tipping screen.
Radii of circles are equal to the Probable Error in the first maximum yaw as indicated by each corresponding group of shots.
+ = Tipping Screen at Minimum Yaw Position.
□ = Tipping Screen at Maximum Yaw Position.
$\bar{\delta}_M$
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
0°
20°
40°
60°
Angle of Impact


Effect of Angle of Impact
Caliber .50
+ = 1/8" Dural.
✕ = 0.0475" Steel.
⊡ = 0.0951" Steel.
δ̄M = Average first maximum yaw after penetrating tipping screen.
Radii of circles are equal to the Probable Error in the first maximum yaw as indicated by each corresponding group of shots.
δ̄M
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
0°
20°
40°
60°
Angle of Impact
4 CORES
1/8" Brass CORES
1/8" Cu
1/16" Dural
Czech Helmet
1/8" Al
1/8" Brass
1/8" Cu

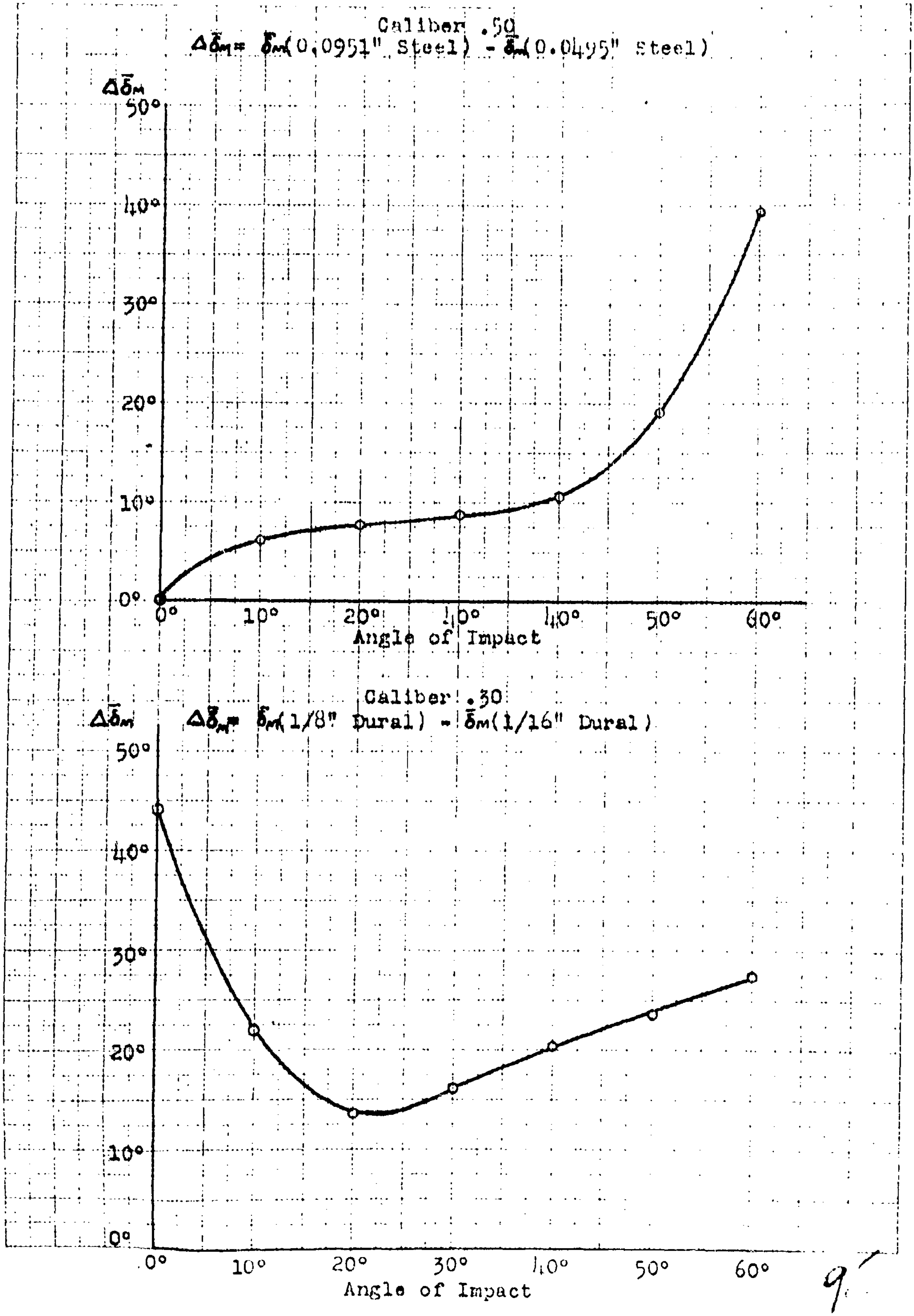

Caliber .50
$\Delta\bar{\delta}_M = \bar{\delta}_M$(0.0951" Steel) - $\bar{\delta}_M$(0.0495" Steel)
$\Delta\bar{\delta}_M$
50°
40°
30°
20°
10°
0°
0°
10°
20°
30°
40°
50°
60°
Angle of Impact
Caliber .30
$\Delta\bar{\delta}_M$
$\Delta\bar{\delta}_M = \bar{\delta}_M$(1/8" Dural) - $\bar{\delta}_M$(1/16" Dural)
50°
40°
30°
20°
10°
0°
0°
10°
20°
30°
40°
50°
60°
Angle of Impact

Figure 74

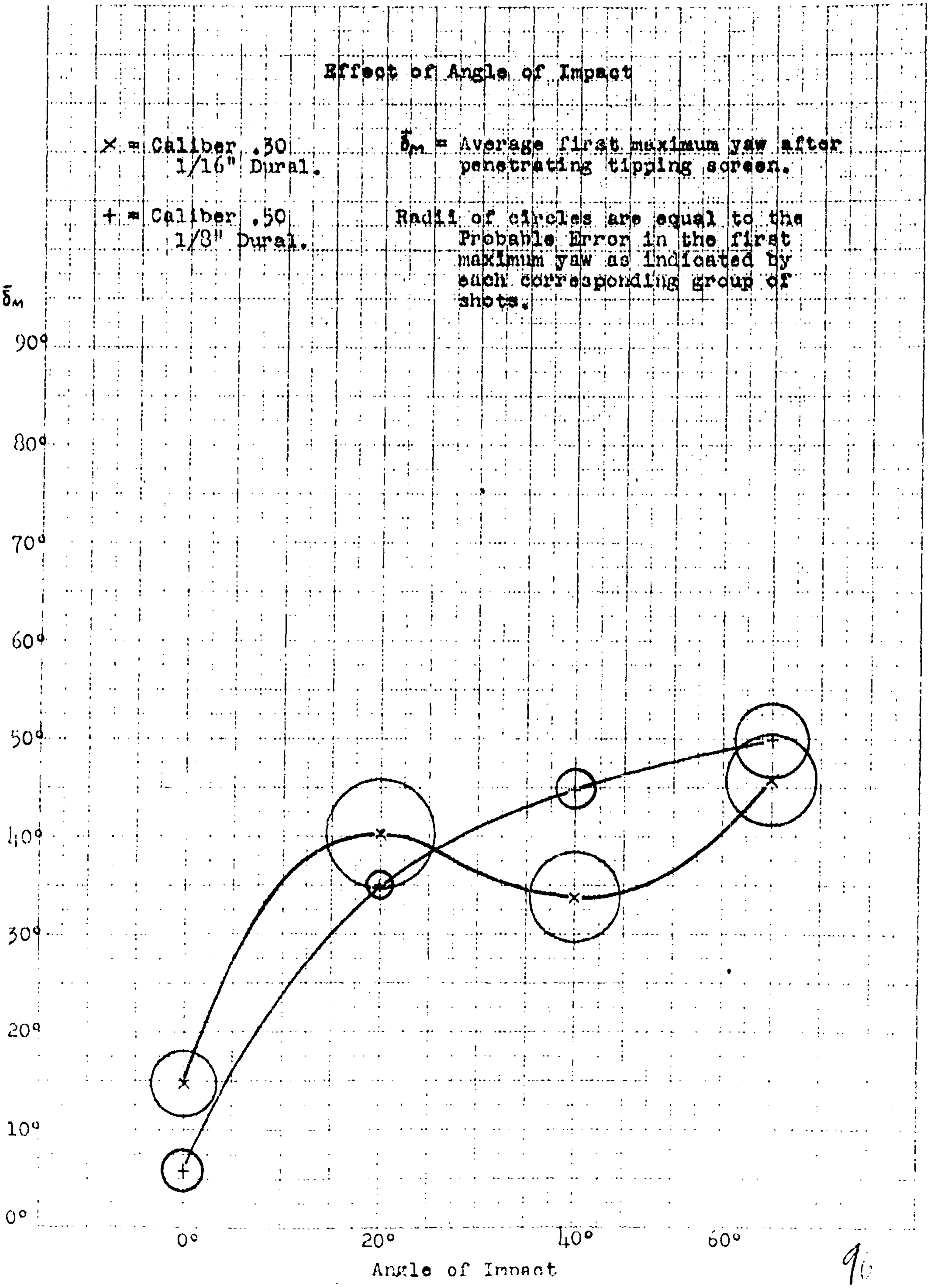
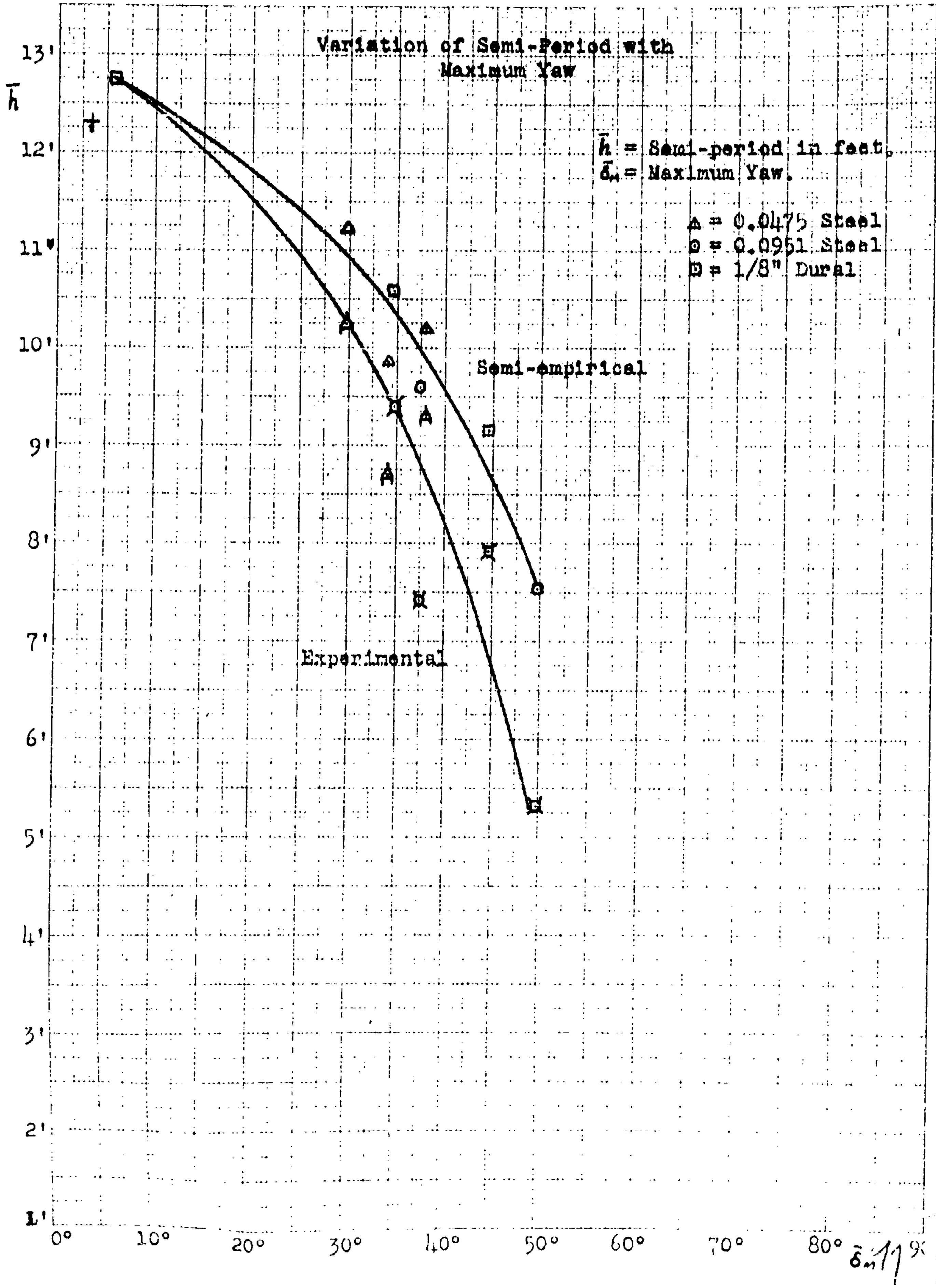

Effect of Angle of Impact
× = Caliber .30 1/16" Dural.
+ = Caliber .50 1/8" Dural.
$\bar{\delta}_M$ = Average first maximum yaw after penetrating tipping screen.
Radii of circles are equal to the Probable Error in the first maximum yaw as indicated by each corresponding group of shots.
$\bar{\delta}_M$
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
0°
20°
40°
60°
Angle of Impact

Figure 75


Variation of Semi-Period with Maximum Yaw
$\bar{h}$ = Semi-period in feet.
$\bar{\delta}_m$ = Maximum Yaw.
△ = 0.0475 Steel
○ = 0.0951 Steel
□ = 1/8" Dural
Semi-empirical
Experimental
$\bar{h}$
13'
12'
11'
10'
9'
8'
7'
6'
5'
4'
3'
2'
1'
0°
10°
20°
30°
40°
50°
60°
70°
80°
$\bar{\delta}_m$

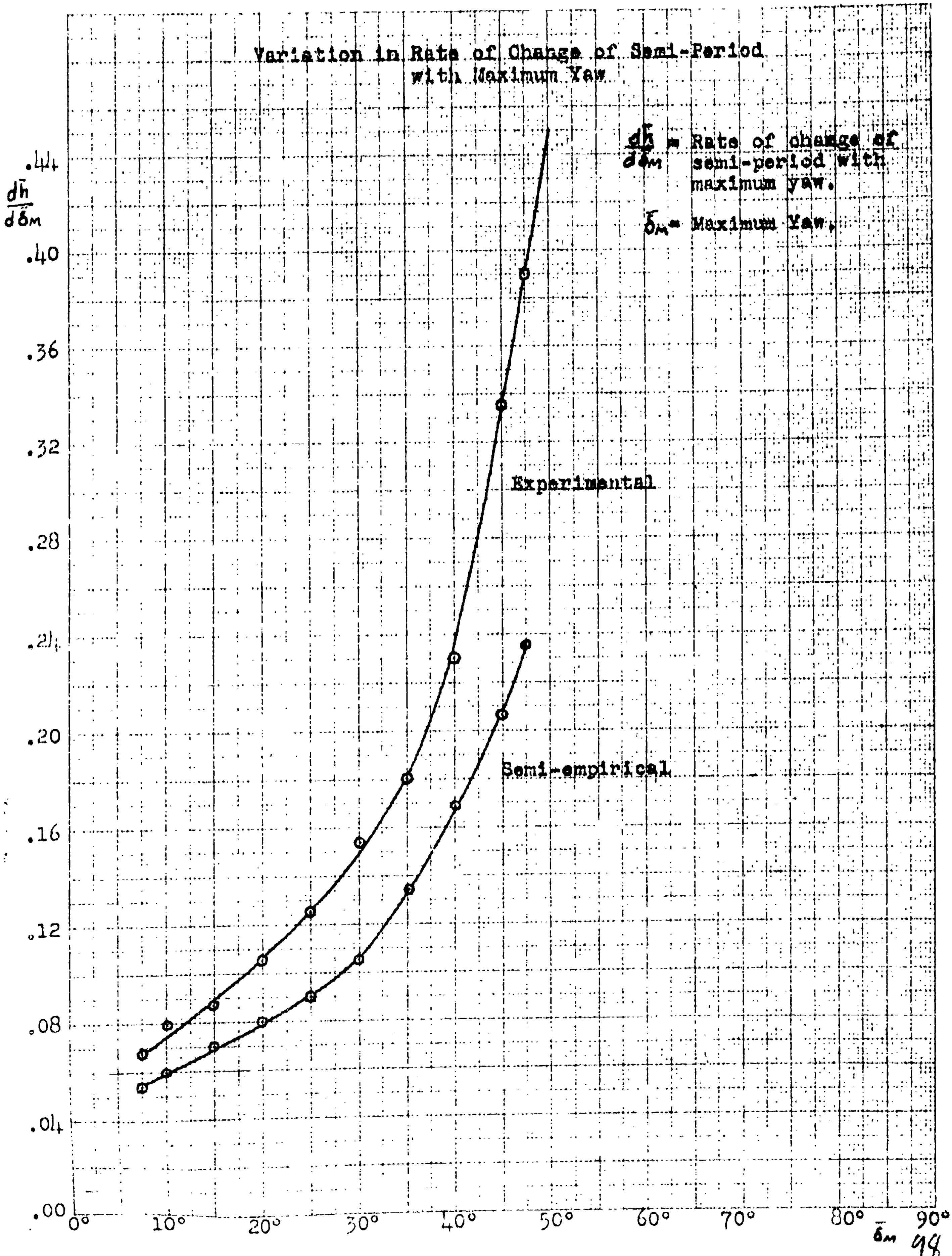
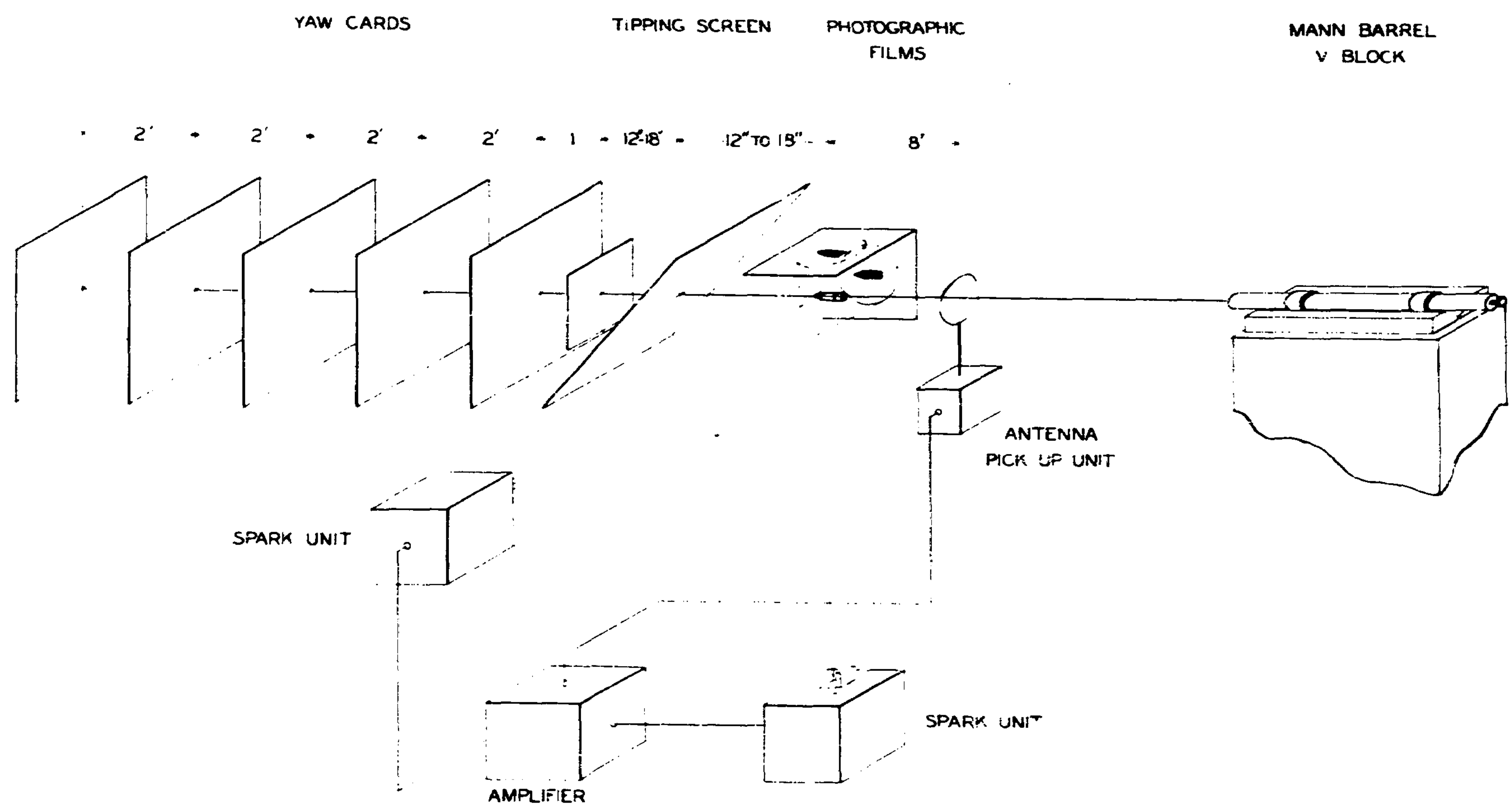
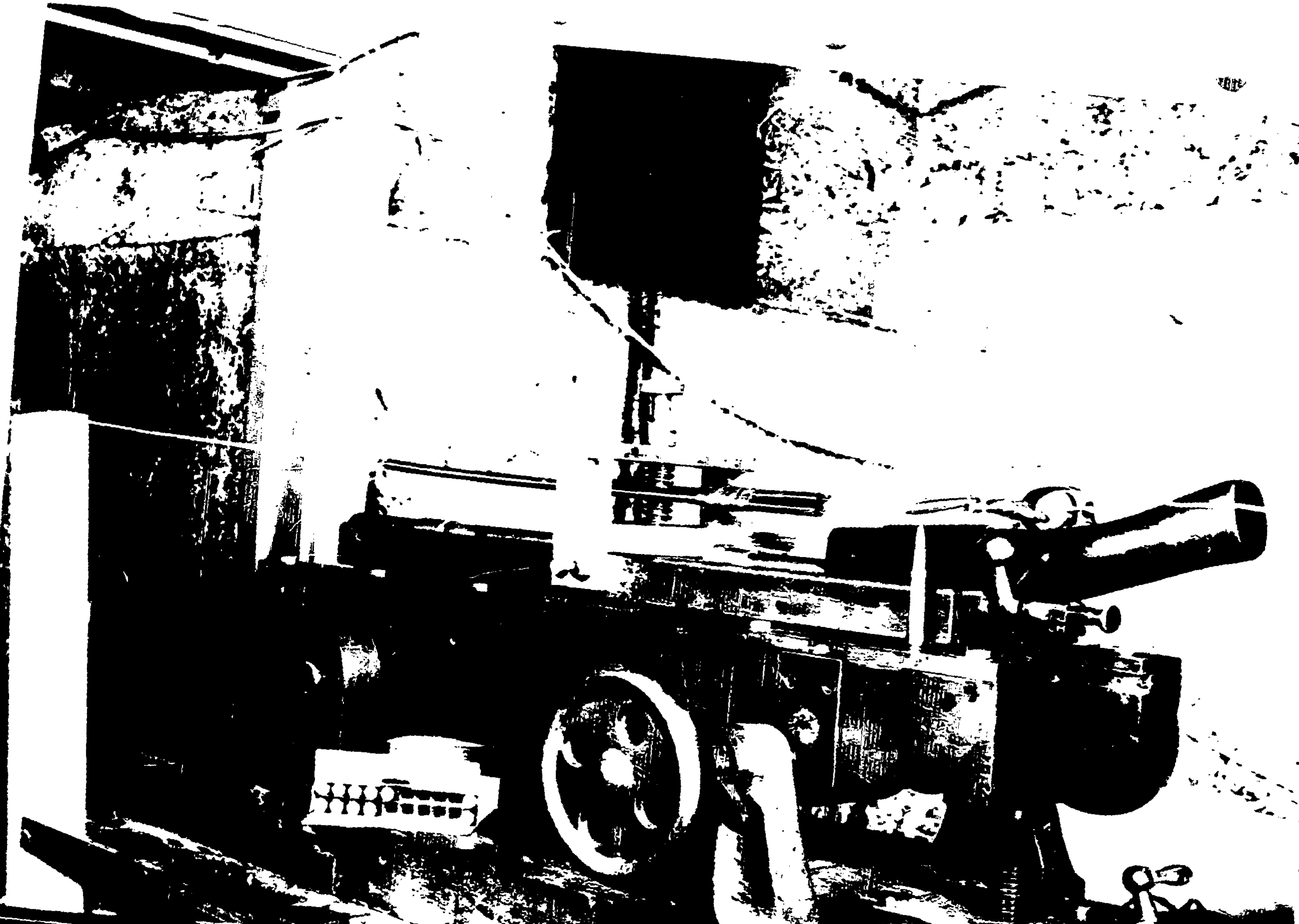

Variation in Rate of Change of Semi-Period
with Maximum Yaw
$\frac{d\bar{h}}{d\bar{\delta}_M}$ = Rate of change of semi-period with maximum yaw.
$\bar{\delta}_M$ = Maximum Yaw.
$\frac{d\bar{h}}{d\bar{\delta}_M}$
.44
.40
.36
.32
.28
.24
.20
.16
.12
.08
.04
.00
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
$\bar{\delta}_M$
Experimental
Semi-empirical

Figure 1

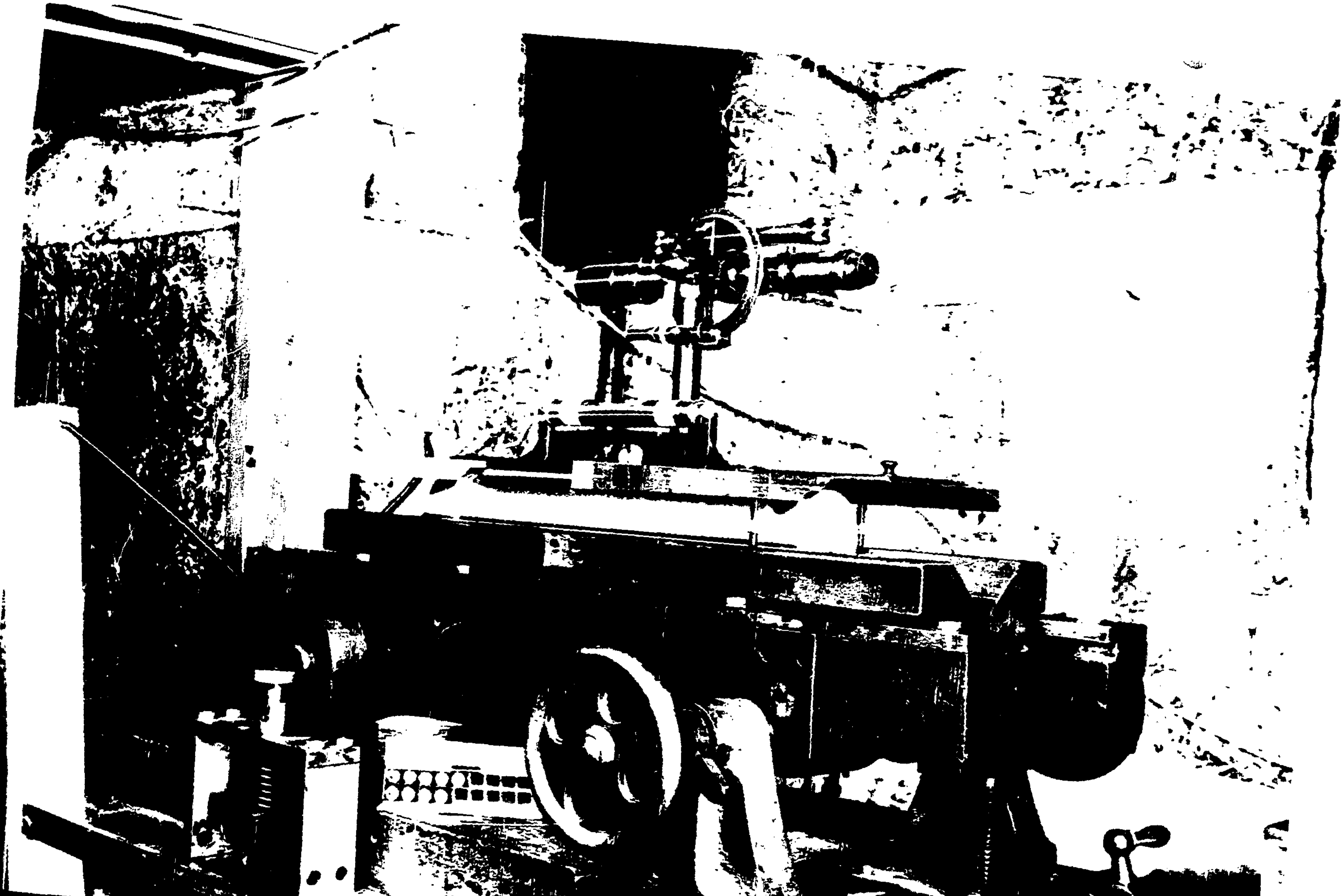
EXPERIMENTAL APPARATUS





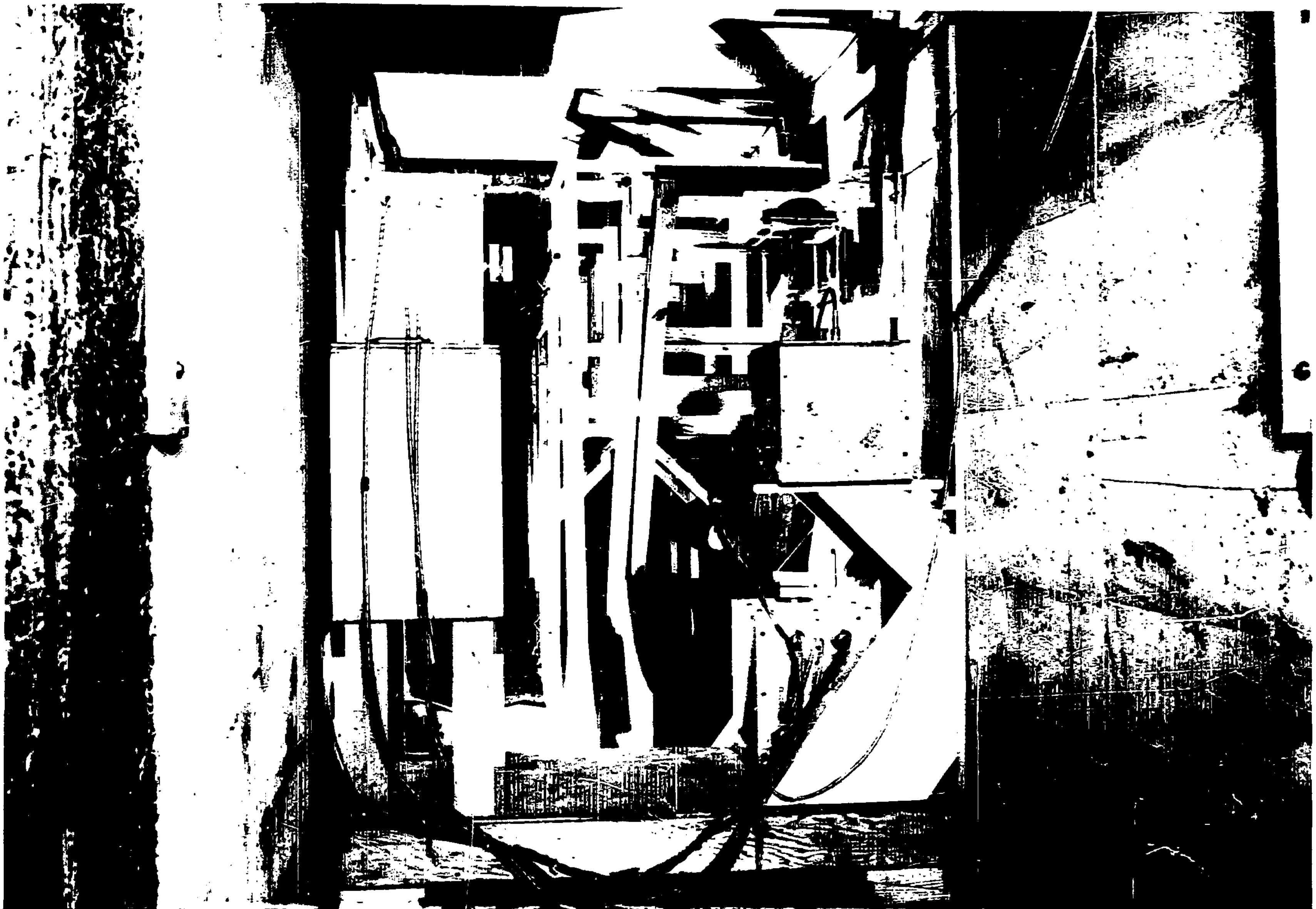
42189 11-14-40 ABERDEEN PROVING GROUND Ordnance Dep't.

RESTRICTED. Close up of Mann Accuracy Barrel, V Block, and Frankfort Rest.



42190 11-14-40 ABERDEEN PROVING GROUND Ordnance Dep't.

RESTRICTED. Close up of Dummy Mann Barrel and Alidade in V Block.



42187 11-14-40 ABERDEEN PROVING GROUND Ordnance Dep't.

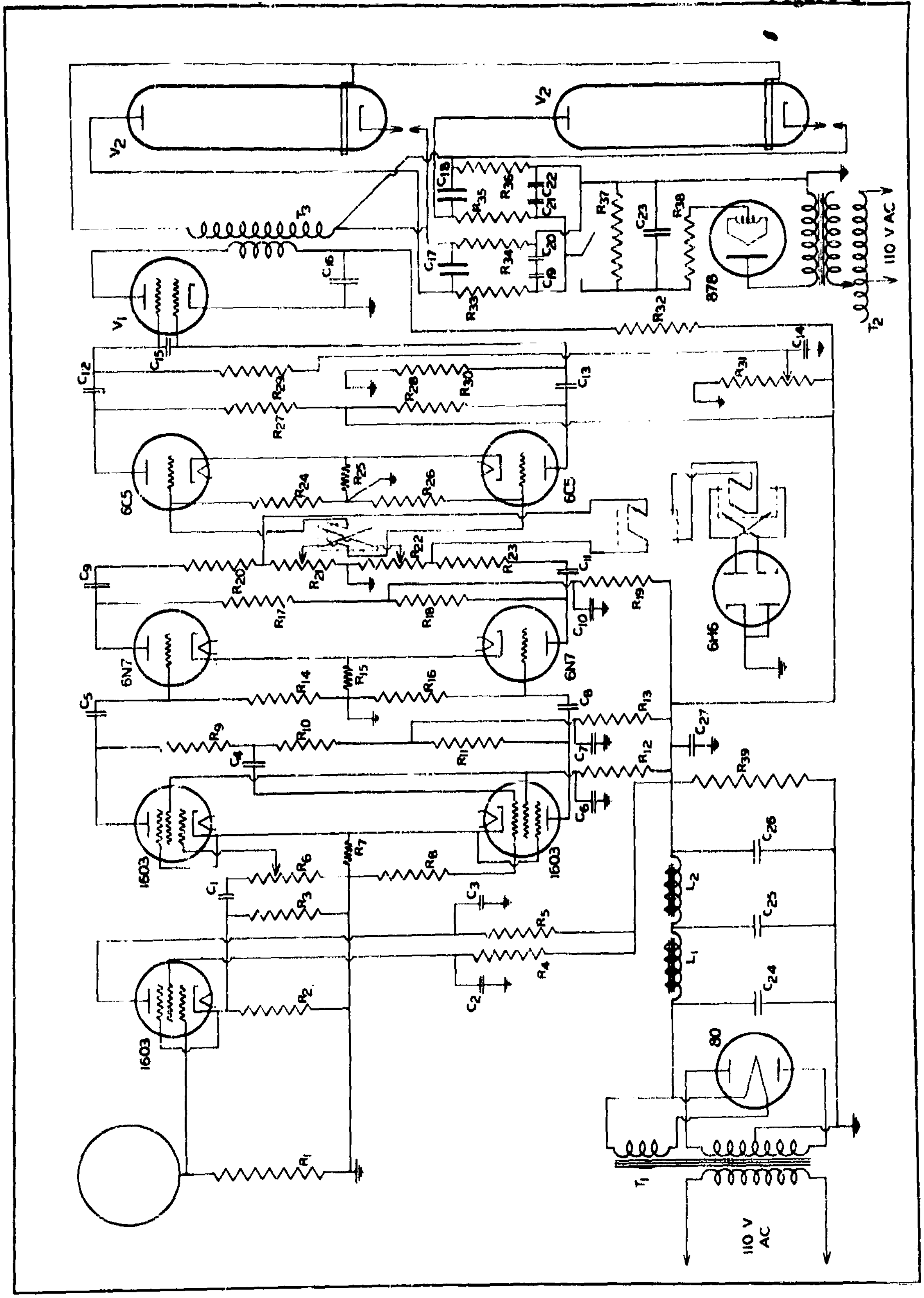
RESTRICTED. Spark photography setup showing spark units, film holders, tipping plate holder, and yaw card [illegible]es.

PHYSICAL PROPERTIES OF TIPPING SCREEN MATERIALS

Material	Thickness	Density lbs/cu.ft.	Density lbs/cu.in.	Weight Unit Area lbs/sq.ft.	Equiv. Thick of Dural Inches	Ultimate Tensile Strength lbs/sq.in.	Strength Weight Ratio Inches
Aluminum soft	1/8" (.124")	174.4	.098	1.80	1/8"	15,000	154,000
Copper hard	1/8"	555.6	.322	5.79	0.392	60,000	186,000
Brass hard	1/8"	524.4	.303	5.46	0.370	60,000	198,000
Dural 24 St	1/16" (.067")	177.0	.100	0.99	1/16"	68,000	680,000
Dural 24 St	1/8" (.128")	177.0	.100	1.86	1/8"	68,000	680,000
Steel 1020	0.0475"	490.7	.308	1.94	.132	66,000	214,000
Steel 1020	0.0951"	490.7	.308	3.89	.264	66,000	214,000
Czech Helmet Steel	0.047	452.2	.262	1.77	.120	?	?

Figure -5-

Figure 6



V2
V2
T3
V1
878
110 V AC
T2
6C5
6C5
6N7
6N7
6H6
1603
1603
1603
80
T1
110 V
AC

Resistors

R_1 = 5 megohms
R_2 = 2000 ohms
R_3 = 2000 ohms
R_4 = 500,000 ohms
R_5 = 100,000 ohms
R_6 = 250,000 ohm potentiometer
R_7 = 750 ohms
R_8 = 250,000 ohms
R_9 = 75,000 ohms
R_{10} = 750 ohms
R_{11} = 75,000 ohms
R_{12} = 250,000 ohms
R_{13} = 25,000 ohms
R_{14} = 250,000 ohms
R_{15} = 3000 ohms
R_{16} = 250,000 ohms
R_{17} = 200,000 ohms
R_{18} = 200,000 ohms
R_{19} = 25,000
R_{20} = 100,000 ohms
R_{21} = 250,000 ohm potentiometer
R_{22} = 250,000 ohm potentiometer
R_{23} = 100,000 ohms
R_{24} = 500,000 ohms
R_{25} = 2000 ohms
R_{26} = 500,000 ohms
R_{27} = 100,000 ohms
R_{28} = 100,000 ohms
R_{29} = 250,000 ohms
R_{30} = 250,000 ohms
R_{31} = 15,000 ohm potentiometer
R_{32} = 250,000 ohms
R_{33} = 1 megohm
R_{34} = 1 megohm
R_{35} = 1 megohm
R_{36} = 1 megohm
R_{37} = 4 megohms
R_{38} = 200,000 ohms
R_{39} = 25,000 ohms

Condensers

C_1 = 0.01 μf
C_2 = 0.1 μf
C_3 = 1.0 μf
C_4 = 0.01 μf
C_5 = 0.01 μf
C_6 = 0.01 μf
C_7 = 2.0 μf
C_8 = 0.01 μf
C_9 = 0.01 μf
C_{10} = 1.0 μf
C_{11} = 0.01 μf
C_{12} = 0.025 μf
C_{13} = 0.025 μf
C_{14} = 0.1 μf
C_{15} = 0.0001 μf
C_{16} = 15.0 μf
C_{17} = 1.0 μf
C_{18} = 1.0 μf
C_{19} = 0.01 μf
C_{20} = 0.01 μf
C_{21} = 0.01 μf
C_{22} = 0.01 μf
C_{23} = 0.5 μf
C_{24} = 1.0 μf
C_{25} = 8.0 μf
C_{26} = 16.0 μf
C_{27} = 0.025 μf

Chokes

L_1 = 5 - 20 h. swing

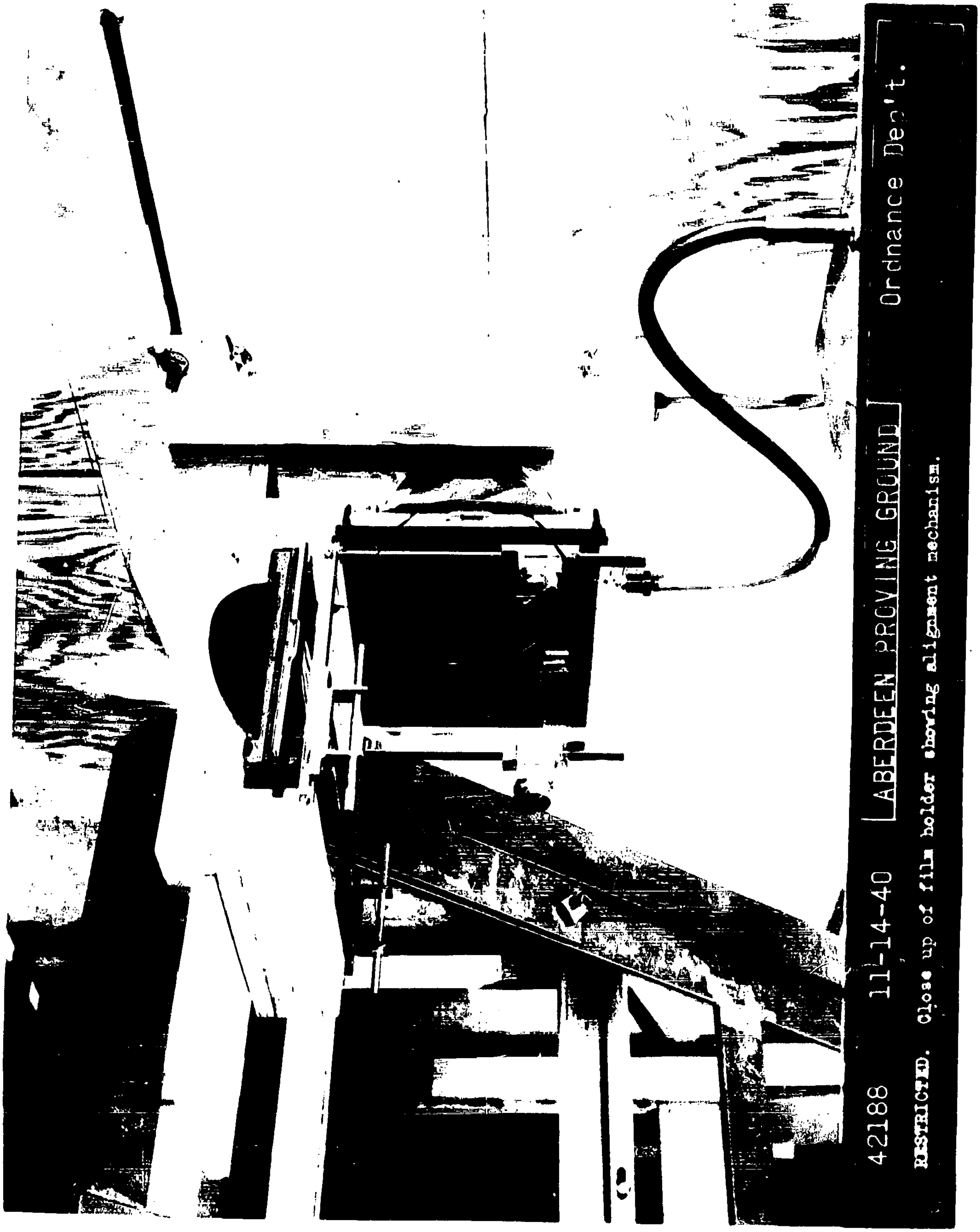
L_2 = 12 h

Transformers

T_1 = Audio Development Co. A1584, 400-0-400.V.

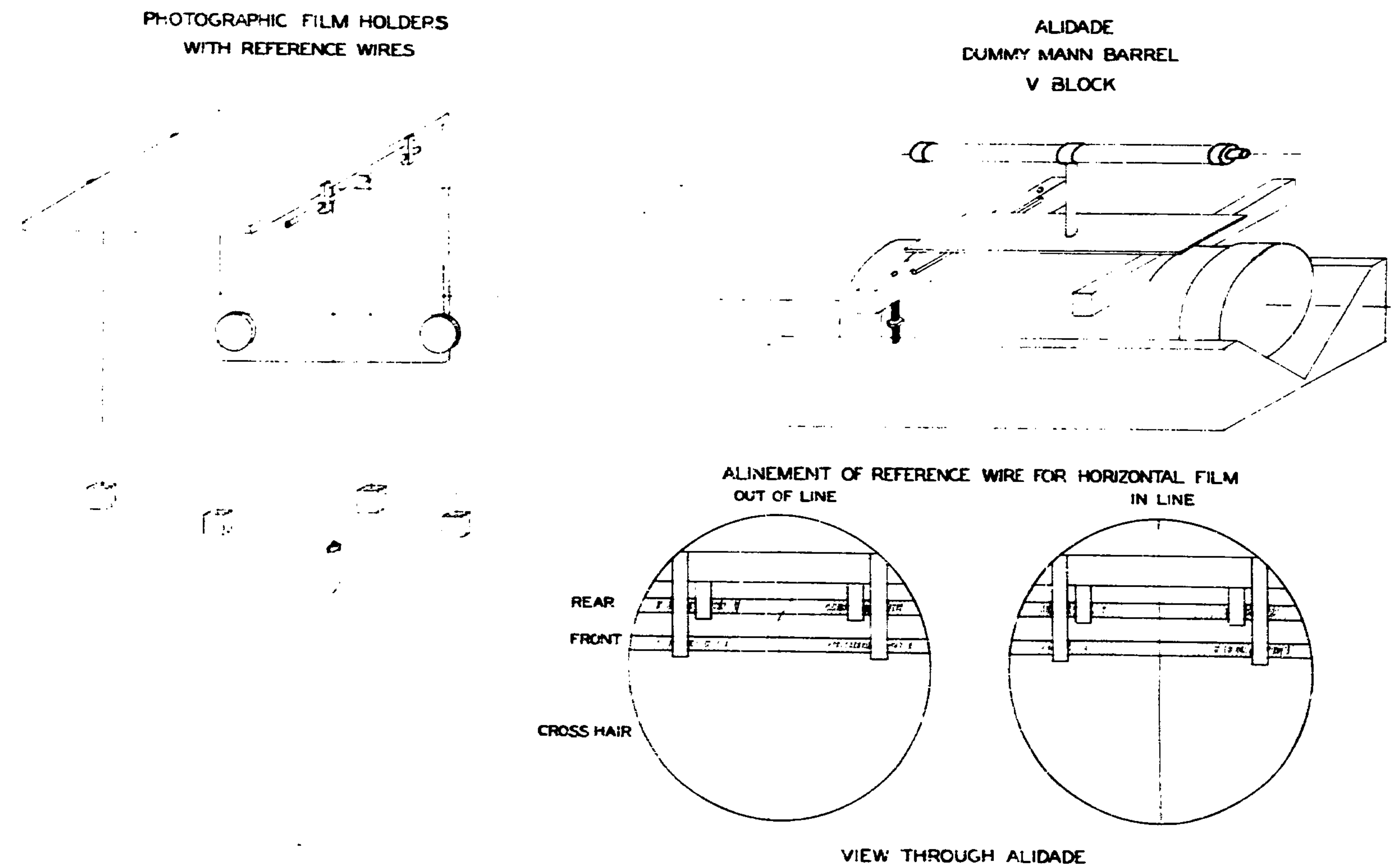
T_2 = Thordarson, T16 R51, 6000 V, R.M.S.

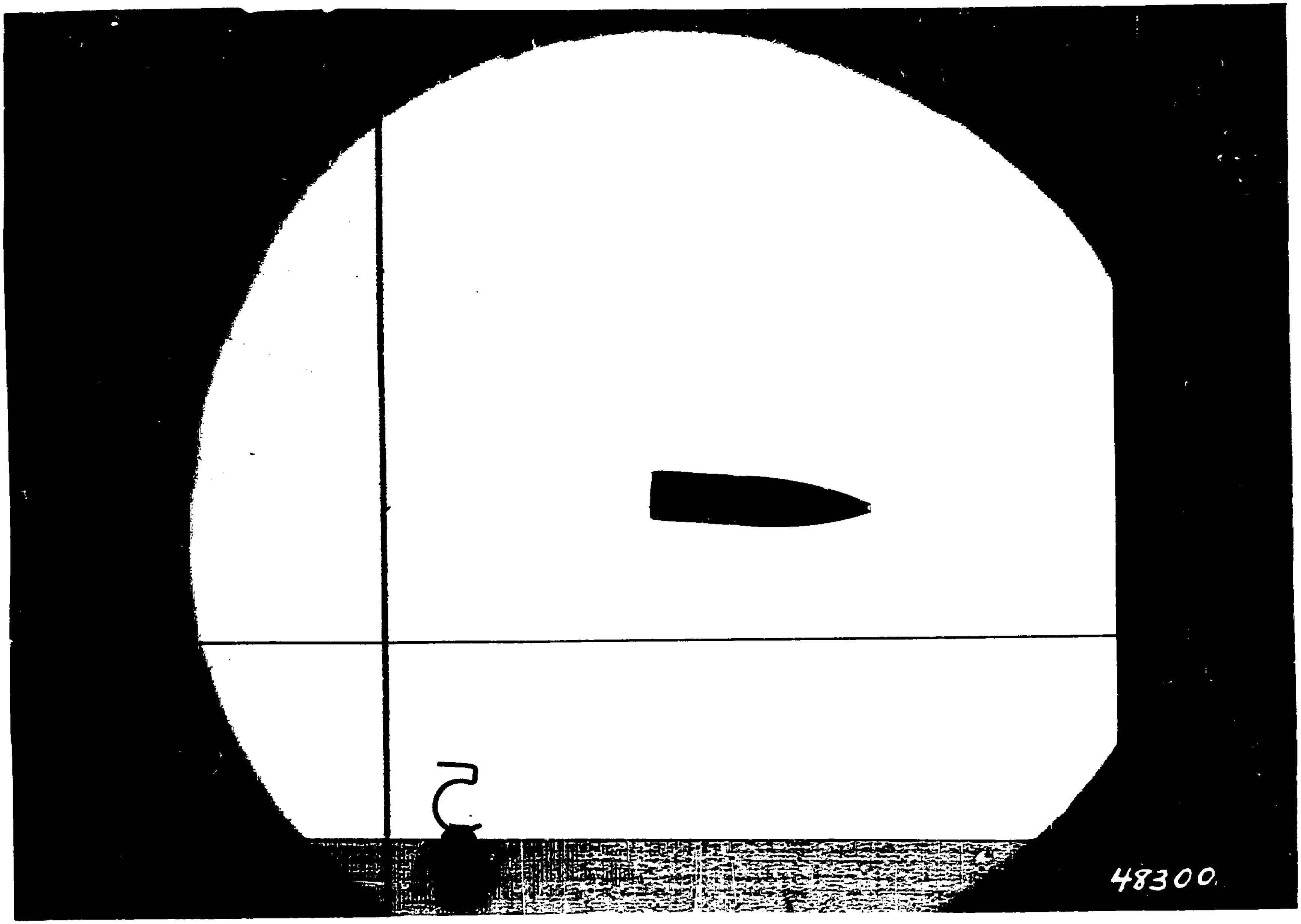
T_3 = Aberdeen Coil.



RESTRICTED. Close up of film holder showing alignment mechanism.

ALINEMENT TECHNIQUE

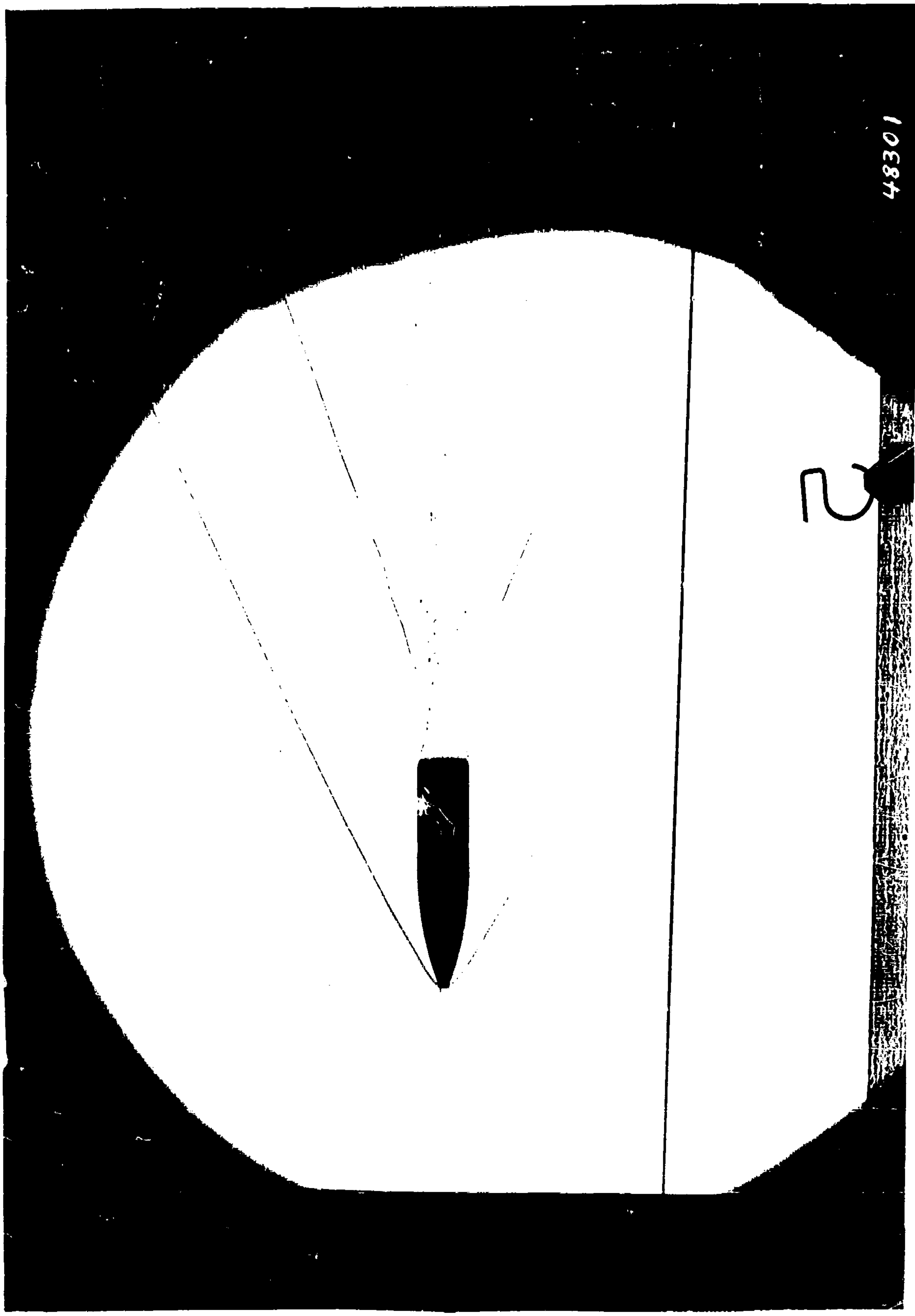




Projectile, Caliber .30 M1922 AP Service Velocity
Projection on Vertical Film

$\zeta = 1°50'$ $\tau = 4°15'$ $\delta = 4°40'$ $\varpi = 203°20'$

Figure 12



Projectile, Caliber .30 M1922 AP Service Velocity
Projection on Horizontal Film

$\zeta = 1°50'$ $\eta = 4°15'$ $\delta = 4°40'$ $\varphi = 203°20'$

DEPARTMENT OF THE ARMY
US ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND
ARMY RESEARCH LABORATORY
ABERDEEN PROVING GROUND MD 21005-5066

AMSRD-ARL-O-IO-SC (APG) (380) 4 October 2005

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SUBJECT: Distribution Statement - Ballistic Research Laboratories Memorandum Report No. 220

1. Reference: Ballistic Research Laboratories Report No. 220, "Characteristics of Tipping Screens", A. C. Charters, Jr., July 1941, UNCLASSIFIED, AD no. ATI 41998.

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Douglas J. Kingsley
for CONSTANCE L. BERRY
Team Leader
Security/CI Office

TITLE: Characteristics of Tipping Screens (Carried out under OP5439)	ATI-41998
AUTHOR(S): Charters, A. C.	REVISION (None)
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ABSTRACT:

A series of light, metal plates, called " Tipping Screens", were subjected to fire by caliber .30 and .50 projectiles to determine their ballistic characteristics. Tipping screens of duraluminum, steel, brass, copper and soft aluminum were tested at angles of impact from 0° to 60°. The yaw of the projectiles were measured just prior to impact with the screen and for some distance beyond. It was found that relatively light screens will produce a large yaw, 40° to 60°, but that a distance approximately equal to 1/2 of an ordinary semiperiod is required for the yaw to develop. The yaw produced by the screen is independent of the angular velocity and the yaw of the projectile at the time of impact. It depends on the material, thickness, and angle of impact of the screen, and the physical properties of the projectile. The optimum material of those tested is duraluminum; however, steel shows promise of equal performance if its strength-weight ratio is increased sufficiently.

Noforn, auth: BRL/APG, 27 Oct 67

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